# San Francisco RNP to GLS Demonstration

*18 November 2016*

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# Executive Summary

In August 2016, Delta Air Lines and United Airlines flew two Boeing 737-900ERs in a series of precision approaches into San Francisco International Airport (SFO). The objective of these flights was to improve airport efficiency at SFO with new approach procedures. One procedure features a much shorter turn to final approach, reduces the distance flown by twenty nautical miles and time spent in the air, cuts emissions by up to 1700 lbs per approach, avoids nearby Oakland Airspace, and improves community noise exposure for several densely populated East Bay communities. Other procedures could reduce the ceiling and visibility requirements for simultaneous parallel runway approaches and optimize air traffic control workload while maintaining a high rate of arrivals in poor weather conditions.

This demonstration focused on the benefits of linking two, high precision satellite-based approach technologies – Required Navigation Performance (RNP) and Global Navigation Satellite System (GNSS) Landing System (GLS). The demonstration was an industry effort and brought together teams from SFO, the FAA Northern California TRACON (NCT), Delta Air Lines, United Airlines, Jeppesen and Boeing. It enabled stakeholders to study the benefits of the approaches, evaluate the performance of the procedures, and understand infrastructure impacts of GLS operations to accelerate the implementation of RNP to GLS.

For SFO, RNP procedures alone can reduce community noise and reduce fuel burn and emissions by flying shorter, more direct routes away from noise sensitive areas. GLS final precision approach segments are in use today at several airports worldwide. While both RNP and GLS can be used separately, the greatest operational benefits are achieved when an RNP approach terminates in a GLS final segment, designated an RNP to GLS procedure. RNP to GLS operations offer capabilities beyond what is available with existing airport precision approach tools invented 85 years ago. RNP to GLS procedure can reduce the approach minima and enable more efficiency by allowing simultaneous operations in lower ceiling and visibility conditions. In addition, the combination of a higher glideslope and touchdown points further down the runway (e.g., displaced threshold) can increase vertical separation between two streams of traffic to allow for more efficient simultaneous parallel operations. One of the new procedures demonstrated could potentially remove an air traffic control sequencing constraint that requires heavy-sized aircraft to use only one runway during some simultaneous approaches, thus reducing controller workload. RNP to GLS procedures could be implemented to other runways, adding precision approach capability where none exists today, further increasing airport all-weather access.

SFO is the seventh busiest airport in the United States, handling over 400,000 movements annually. To accommodate traffic demands, SFO typically operates simultaneous departures and arrivals to runways 28L and 28R. During low visibility conditions, which occur up to 23 percent of time annually, the airport must operate single stream arrivals which significantly increases delays and reduces airport access. There are no precision approaches to runways 10L or 19R due to proximity of rising terrain and airport infrastructure, respectively. Furthermore, RNP to GLS procedures can be designed to define clean, quiet, and efficient approach profiles. These low energy approaches are designed with special attention to the altitude profile, airspeed, descent rates, aircraft configuration (e.g., flaps and landing gear setting), and the engine thrust level. By managing these parameters, approaches can be designed to minimize the use of speedbrakes and level segments, both of which contribute to community noise and emissions.

This report contains a summary of SFO operations today, an overview of RNP and GLS technology, RNP to GLS procedure design, flight demonstration coordination, environmental performance assessment and next steps to implement RNP to GLS procedures. In the near term, the team recommends that SFO implements RNP procedures to runways 10L and 19R to improve efficiency in the airspace. In the long term, SFO should install a GLS ground station and implement RNP to GLS procedures to improve simultaneous operations to runways 28L/28R, and add precision approaches to runways 10L and 19R.

 

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# 1 RNP to GLS Technology Overview

This demonstration project focused on two technologies – Required Navigation Performance (RNP) and the Global Navigation Satellite System (GNSS) Landing System (GLS). RNP is a form of performance-based navigation (PBN) that allows an aircraft to fly a predefined, three dimensional (3D) path. RNP differs from area navigation (RNAV) in that the aircraft monitors its position using GPS. If the aircraft senses it is beyond a required specification (i.e., track boundary), it alerts the pilot. RNP specification can be large or small - from 10 to 0.1 nautical miles (nm). Smaller RNP specification enables reduced separation and more precise procedures.

GLS enables precision approaches in all weather conditions, a similar capability to the Instrument Landing System (ILS). Precision approach implies both lateral and vertical guidance. However, instead of a ground based localizer and glideslope antennae that comprise the ILS, GLS uses navigation satellites, such as GPS, GLONASS, or Galileo for precision approaches in all weather conditions. GLS has three components; navigation satellites, aircraft avionics and an airport ground based augmentation system (GBAS) station. A single airport GBAS sends differential corrections to each aircraft near the airport to enable precision approach. GLS avionics are available for most transport aircraft platforms today.

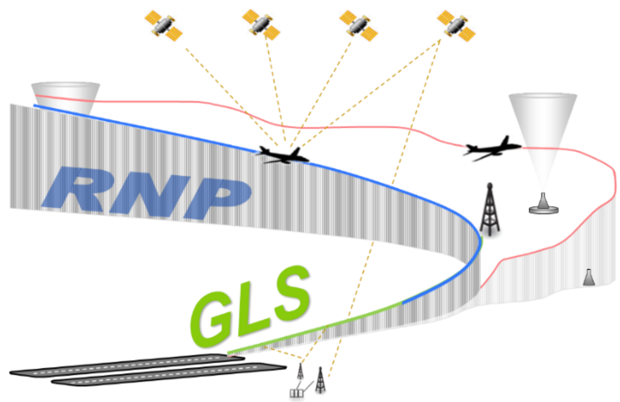



*Figure 1: RNP to GLS Overview*

GLS and GBAS offer several operational benefits over ILS. In poor weather, airport efficiency suffers due to limitations of ILS. Areas near the glideslope antenna must be protected from taxiing aircraft to prevent interference with the ILS signals. This increases taxi time for departing aircraft. In addition, it is challenging and sometimes impossible to site an ILS in areas with sharply rising terrain, or other infrastructure obstacles (e.g., buildings, parking garages). Furthermore, ILS generally requires aircraft to fly long, straight-in final approaches to allow the aircraft time to capture lateral and vertical guidance and stabilize the approach. This longer path at a lower altitude increases fuel burn, emissions and community noise. To maximize efficiency in all weather conditions, ILS installations are required on each runway end which can be expensive to install and maintain. On the other hand, a single GBAS station can provide up to 48 approaches and therefore accommodate every landing runway end.

The combination of RNP and GLS as the integrated solution for approach and landing can reduce delays while increasing efficiency. With RNP to GLS, a single, efficient path can be used in all-weather to make traffic flow more predictable and enhance safety. RNP to GLS procedures can be tailored to meet specific airspace constraints. The following summarizes the operational benefits of RNP to GLS procedures:

- Enabling precise navigation in obstacle-rich areas in reduced visibility where ILS is not possible
- Reducing track miles flown by enabling shorter final approach segments, saving fuel and emissions
- Allowing flexible, curved paths to reduce community noise exposure
- Increasing access during lower weather minima reducing the risk of diversion, cancellations
- Implementing efficient aircraft separation and spacing (for parallel approaches)
- Providing multiple glideslopes and alternate touchdown points for wake vortex mitigation
- Supporting multiple GLS procedures with single GBAS
- Eliminate false and mirror glideslopes and ILS beam bending
- Reducing ILS critical areas

## 2 San Francisco Operations Today

SFO is the 7th busiest airport in the US[1]and serves as a major hub for United Airlines. It is also 4th in the US for delays according to the *Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe* published by the European Commission, EUROCONTROL and the FAA in 2016.[2] SFO has two pairs of runways that cross, spaced just 750 feet apart as shown in Figure 2. ILS guidance is only available to runways 28L/28R, and 19L.


*Figure 2: SFO Aerial View (Source SFO)*

Today, there are approximately 1300 daily operations at SFO. Nearly all operations occur between 0600 local and midnight. In addition to serving as a connecting hub for United Airlines, the airport supports extensive trans-Pacific and other international aircraft. Flights are concentrated in four to five 'banks' through the 18 hour operating day. These banks create spikes in demand that exceed 40 arrivals and departures per hour according to *SFO's Strategic Plan to Improve On-Time Performance*[3]. SFO predicts further increases in airport demand, citing a 10% growth in international traffic annually. When ceiling and visibility weather conditions support visual operations, the airport can easily accommodate peak demand with minimal delays by operating simultaneous arrivals and simultaneous departures. Air traffic control (ATC) routinely pairs arrivals using visual separation with sufficient spacing between pairs to allow simultaneous departures.

Generally, aircraft depart on runways 01L/01R and arrive on runways 28L/28R. During weather periods that exceed a 3000 feet ceiling and five statute mile (sm) visibility, air traffic controllers sequence arrivals to runways 28L and 28R utilizing visual separation between aircraft, which can allow a peak arrival rate of 56 per hour. Weather conditions below 3000 feet ceilings and/or five sm visibility (this is called instrument meteorological conditions or IMC) require the use of various instrument approach procedures that limit airport efficiency to 28 to 36 arrivals per hour.

Table 1 presents the length, width, Precision Approach Category, and annual percentage of arrivals for each runway end. Precision Approach Path Indicators (PAPI) are installed on runways on runways 10L/10R, 19L/19R, and 28L/28R. There are no PAPI installed on runways 01L/01R.

[1] http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/PTFF_Complete.pdf
[2]https://www.eurocontrol.int/publications/2015-comparison-air-traffic-management-related-operational-performance-usa-and-europe
[3] http://apps.mtc.ca.gov/meeting_packet_documents/agenda_1736/09232011RAPC_SFO_v1.pdf

*Table 1: Runway Dimensions, Approach Capability and Landing Statistics*

| Runway | Dimensions | Precision Approach Category and Lighting | Annual Arrivals for Each Runway End |
|---|---|---|---|
| **01R** | 8650 x 200 ft. | No ILS –No PAPI | 0.04% |
| **01L** | 7650 x 200 ft. | No ILS – No PAPI | 0.06% |
| **10R** | 11381 x 200 ft. | No ILS – PAPI | 0.24% |
| **10L** | 11870 x 200 ft. | No ILS – PAPI | 0.37% |
| **19R** | 7650 x 200 ft. | No ILS – PAPI | 1.56% |
| **19L** | 8650 x 200 ft. | CAT I ILS – PAPI | 4.02% |
| **28R** | 11870 x 200 ft. | CAT III ILS – PAPI | 55.69% |
| **28L** | 11381 x 200 ft. | SA CAT II – PAPI | 38.02% |

The marine climate in the San Francisco Bay area creates frequent and unpredictable periods of low ceilings that prevent the use of visual separation between arrivals on runways 28L and 28R. To improve operations in these weather conditions, the airport, FAA and the operators have developed procedures that allow greater use of visual separation and increase the single runway arrival rate. With these new procedures, airport arrival rates can exceed the single runway arrival rate that is normally imposed (i.e., when visual separation between arrivals is not possible). This included research for methods to safely reduce legacy wake turbulence separation standards when arriving or departing the closely spaced parallel runways.

## 2.1 Visual Operations

At SFO, the most favorable “visual” operating configuration occurs when winds permit landing on runways 28L/28R and departing on runways 01L/01R. Typically, tower controllers will simultaneously release two aircraft for takeoff on runways 01L/ 01R. To ensure the departing airplanes are separated from arriving aircraft on the crossing runways, air traffic controllers space out arriving pairs of aircraft on runway 28L/28R to create ‘windows’ for the two departing aircraft to safely cross the intersecting runway centerlines. The size of the ‘window’ is dictated by the time needed for the departures to fly through the runway 28L/ 28R intersections before the lead arriving aircraft crosses the landing threshold. Note: Super heavy class aircraft require separation of 8 nm and are not paired with any other aircraft.[4]

In less than visual conditions, wake turbulence separation requirements for closely spaced parallel runways can severely reduce airport throughput, particularly during periods of peak demand. Essentially, the parallel runways must be treated as a single runway for separation purposes reducing the arrival rate by almost 50%. Spacing on final approach is determined by the greater of the separation required for wake turbulence or as needed to clear aircraft for takeoff on runways 1L/1R (similarly for the landing runways 19L/19R and departing runways 10L/10R). Depending on the fleet mix of the arrival stream and the departure demand, the advertised arrival rate may be as low as 28 operations per hour. This situation occurs quite frequently during peak morning arrival and departure banks, as morning fog, or the marine layer, will commonly persist until 1100 or 1200 local time. It is not unusual to have daily ground stops or ground delay programs, coupled with holding and extensive vectoring to manage the excess arrival demand. The impacts of these delays are particularly intrusive when they occur in the morning as these delays propagate throughout the day with little opportunity to recover. Delays frequently exceed 90 minutes.

[4] http://www.faa.gov/documentLibrary/media/Order/Final_Wake_Recat_Order.pdf

## 2.2 Typical Landing Operations – Runways 28L/28R

As seen in Figure 3, the majority of the time, “good” weather prevails and ATC is able to utilize visual separation to accommodate peak arrival demand. Capacity at the airport is severely limited by wake turbulence separation requirements and procedures associated with the closely spaced parallel runways causing significant delays and inconvenience. Often the visibility below the marine layer is good. As a result of the unique weather characteristics at SFO, the industry and FAA developed Simultaneous Offset Instrument Approach (SOIA) procedures to recover some of the arrival capacity lost when visual separation is not feasible, but full IMC ATC operating procedures are not required for landing. When the ceiling and visibility do not support SOIA operations, advances in wake turbulence research have enabled some limited reduction in longitudinal separation for dependent approaches to parallel runways spaced less than 2500 feet apart (FAA 7110.308). Table 2 summarizes the operational approach procedures in various weather conditions as SFO.

The next two sections provide more details on these two operations and provide the foundation for understanding the basis and objectives of the procedures flown during the RNP to GLS Demonstration.

Figure 3 shows the annual weather percentages. Over the course of the last 20 years the FAA and airlines have collaborated to develop two sets of rules and procedures to allow some improvements in operations in marginal weather. Marginal weather is defined as ceiling between 1000 feet and 3000 feet with visibility of three to five sm[5].

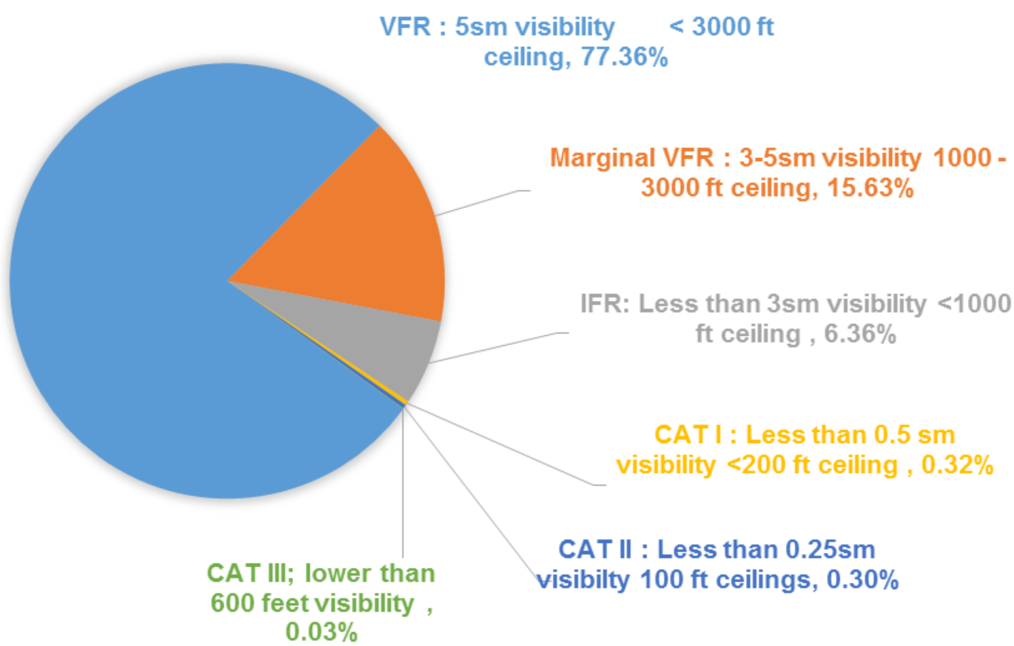



*Figure 3: SFO Ceiling and Visibility Annual Percentages*

[5] http://profhorn.meteor.wisc.edu/wxwise/weather/lesson6/content.html

*Table 2: Weather Conditions Defining Operations at SFO*

| Weather Condition | Ceiling and Visibility | Operational Approach Procedures | Arrival Runways | Advertised Arrival Rate |
|---|---|---|---|---|
| Supporting ATC Issuance of a Visual Clearance | Generally 3500 feet ceiling with 5 sm visibility along extended final approach course. (Reported weather at SFO may not be indicative of conditions on the final approach course) | Simultaneous arrivals and departures under Visual ATC Clearance – pilot responsibility for wake turbulence avoidance | Runways 28L and 28R | 54 operations/hr |
| Marginal -Visual Meteorological Conditions (MVMC) | At or above 1600 feet and 4 sm | Simultaneous Offset Instrument Approaches (SOIA) 28R<br><br>ILS/RNAV 28L | Simultaneous approaches to Runways 28L/28R | 36 operations/hr |
| MVMC & Instrument Meteorological Conditions (IMC) | Above CAT I minima | Simultaneous Dependent Approaches to Closely-Spaced Parallel Runways (CSPO) (FAA Order 7110.308A) | Simultaneous Dependent approaches to Runways 28L/28R | 34 operations/hr |
| Below CAT I Minima | Below 200 feet and below 0.5 sm | Single runway operations | 28R only CAT III, 28L has SA CAT II | 27 operations/hr |

Airports with parallel runways operate by FAA rules to prevent wake turbulence encounters from nearby aircraft. The FAA specifies separation rules and operating procedures for visual flight rules (VFR) and instrument flight rules (IFR).

## 2.3 Simultaneous Offset Instrument Approaches (SOIA)

When the ceiling is at or above 1600 feet, but below conditions that support visual separation between arrivals, SFO can operate Simultaneous Offset Instrument Approaches (SOIA)[6] to runways 28L and 28R. SOIA operations consist of one straight-in final approach course (FAC) and one offset FAC to closely spaced parallel runways. The procedures are designed to allow the trailing aircraft on the offset procedure to descend clear of clouds while still protected by required separation for collision avoidance and wake turbulence avoidance. There is a required visual segment at the end of the SOIA approach to 28R wherein the trailing airplane must have visual reference to both the airport and the lead airplane approaching runway 28L prior to the reaching the decision altitude (DA) or missed approach point (MAP).

SOIA consists of one lead aircraft flying a straight-in, 2.85$^0$ glideslope approach to runway 28L (depicted with the blue dotted/dashed line in Figure 4), and a second trailing aircraft to an offset approach (depicted in green dashed line in Figure 4). The offset approach path to 28R is constructed so that when the aircraft arriving on the offset runway 28R approach reaches a point separated by 3000 feet from the parallel approach path on runway 28L, it transitions to visual flight rules as it begins a gradual turn to align with the extended centerline of runway 28R[7]. The visual maneuver must begin after the missed approach point and is hand-flown with visual references only. The pilot continues the descent after visually acquiring the airport and the lead aircraft on runway 28L and maintains wake separation.

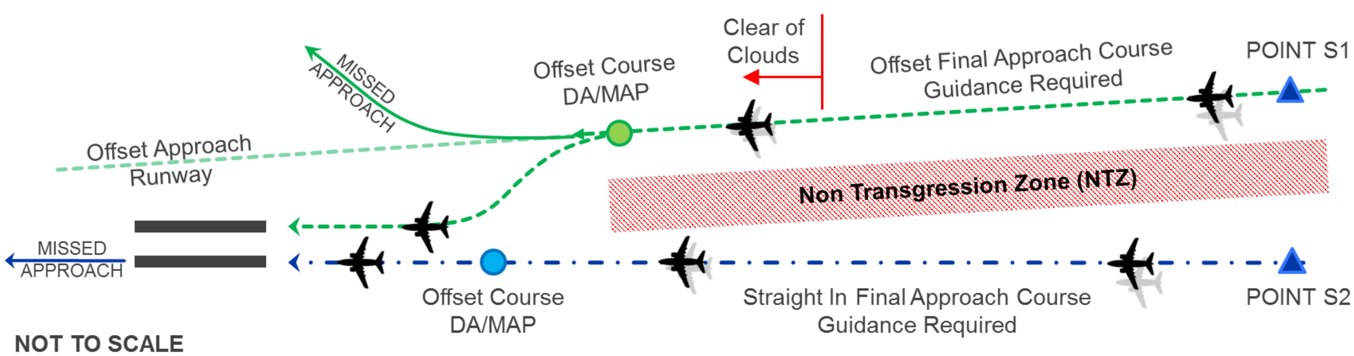



*Figure 4: SOIA Overview Diagram*

SOIA procedures enable the airport to maintain use of both runways at a higher acceptance rate than in a single runway operation. With SOIA, there is no restriction on which aircraft type can lead the pair meaning air traffic controllers from NCT are not required to sort the traffic to 28L and 28R. However, there are two significant factors that limit the benefit of the approach, both tied to the requirement for a visual segment.

First, the required ceiling must be set high enough to allow aircraft to descend on the glidepath below the cloud layer to a point where the runway and the other aircraft are in sight before the lateral separation is reduced to less than 3000 feet. This minimum "clear of clouds" time is a primary procedure design parameter. Initially SOIA weather minima were set at 2100 feet, and then after several years of experience, were reduced to 1600 feet with visibility of five sm. Second, air traffic controllers must create a stagger between aircraft to guarantee longitudinal separation and this in turn creates a 'wider window' of airspace for each arriving pair of aircraft. Typically an arrival rate of 36 per hour is quoted for SOIA, with some arrival rates as high as 38. This can be attained only when ceilings are between 1600 feet and 3000 feet and requires the addition of *two more* controller staff to monitor the non-transgression zone (NTZ).

[6] http://media.flysfo.com/PRM_SOIA_version_1_0.pdf
[7] Note the requirement for 3600 feet lateral separation is relaxed to 3000 feet for runways monitored by high update radar, called Precision Runway Monitoring (PRM) radar

## 2.4 Closely-Spaced Parallel Runway Operations (CSPO)

In marginal weather down to CAT I minima SFO can operate in another simultaneous approach operational concept called Simultaneous Dependent Approaches to Closely-Spaced Parallel Runways (CSPO). This is defined by FAA Order 7110.308A and is also called 1.5-Nautical Mile Dependent Approaches to Parallel Runways Spaced Less Than 2500 Feet Apart[8]. This operation increases the advertised arrival rate by 4 to 7 movements per hour above that of CAT I and allows the airport to continue to land on both runways. While simultaneous operations can continue in marginal weather the mandatory a 1.5 nm stagger between the aircraft landing on the parallel runways is in effect which translates to a larger spacing between departures. The operation uses a relatively new wake turbulence rule that permits controllers to establish pairs of aircraft separated by 'staggered' distances of 1.5 nm diagonally as shown in Figure 5.

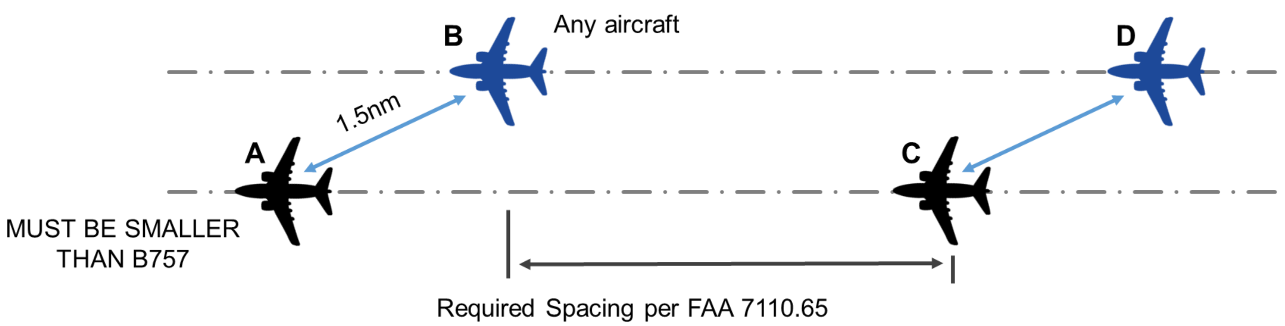



*Figure 5: CSPO Overview*

In the design of the FAA Order 7110.308 procedure for SFO, the ILS glideslope on runway 28L is set at 2.85º, and the glideslope for 28R is set at 3.0º. These different glideslopes provide safe vertical separation behind the wakes of the paired aircraft. The order specifies that air traffic controllers vector the pair of aircraft onto their respective final approach courses, maintaining vertical separation of 1000 feet between the pair until both are established on the final approach. At that point, the pair may proceed on their respective approaches until intercepting their respective glideslopes, then continue using the final approach course guidance down to a decision altitude of 200 feet and land if the runway is in sight.

Unlike the SOIA procedure, there is a restriction on the lead aircraft (landing on runway 28L). Under the CSPO rules, the lead aircraft cannot be B757 or a Heavy (or wake RECAT equivalent)[9]. Manually sorting the aircraft to the 28L stream increases controller workload.

The published advertised arrival rate for the CSPO is 34 operations per hour, nearly the same as SOIA. Occasionally for short periods and with a favorable fleet mix, ATC will exceed that number. The FAA is performing a safety analysis that could amend FAA Order 7110.308 to permit a reduction in diagonal stagger to 1.0 nm, versus the current 1.5 nm. It is expected that this slight reduction in spacing within the pair will further increase the published advertised arrival rate by one or two aircraft per hour. Currently, SOIA yields more operations per hour, however it requires two additional staff to monitor the non-transgression zone (NTZ) and is more complex for pilots and air traffic controllers. There are several benefits to CSPO over SOIA; CSPO approaches do not require the same visual segment as the SOIA, the weather minima can be lower for the CSPO, and CSPO does not require the additional two air traffic controllers to monitor the NTZ of SOIA.

[8] http://www.faa.gov/documentLibrary/media/Order/Order_7110.308A.pdf

[9] Heavy aircraft types of 136,000 kg (300,000 lbs) or more; http://www.icao.int/publications/DOC8643/Pages/default.aspx

## 2.5 CAT I Arrivals to Runways 28L and 28R

CAT I is characterized by very low ceilings or fog, with less ceiling less than 200 feet and 0.5 sm visibility. In these situations, there are CAT II procedures to runway 28L/28R, and a CAT III procedure for runway 28R. These situations require the aircraft to be capable of CAT II/III approaches and special crew training. CAT II/III procedures can only be conducted using a single runway, which limits throughput to no more than 27 operations per hour.

## 2.6 Atypical Landing Operations – Landing to Runway 01L/01R, 10L/10R and 19L/19R

During winter storms exhibiting significant wind and rain with counterclockwise flow from the south and southwest, the airport operates with arrivals on 19L/19R and departures from runways 10L/10R. Runways 19L/19R are only used for landing approximately 5% of the time. For arrivals to 19L/19R, there is only a single ILS CAT I procedure to 19L, and two GPS RNAV approaches. When the weather is below CAT I, arrivals are limited to a single file to the ILS on runway 19L. The long, straight ILS 19L final conflicts with the nearby Oakland International Airport (OAK). In all cases, the arrivals are treated as equivalent to a single runway, with less than 30 operations per hour.

In very rare situations (less than one day annually), high east winds dictate landings on runways 10L/10R. The final approach course flies through a gap with terrain on both sides which dictates very high minima of 1100 feet and 1200 feet MDA(H) (minimum descent altitude). There is one RNP 0.2 procedure to runway 10R which has a MDA(H) just under 400 feet. It is impossible to site an ILS to runways 10L/10R due to their proximity to San Bruno Mountain and rising terrain close to the runway. The only approaches to these runways are visual and only in use when the winds and weather are unfavorable for the other runways. At SFO, most missed approaches are experienced from these runways.

Typically on very warm and clear days, a very strong high-pressure system to the east will create Santa Ana-like winds that dictate arrivals on runways 01L/01R. Presently, there are no instrument approach procedures published for these runways. All approaches are conducted using visual approaches that lack lateral guidance. These challenging wind conditions cause a significant number of missed since these runways are infrequently used and lack precision approach guidance. A special RNAV visual will be published to runway 01R in 2017 to help reduce the number of missed approaches.

# 3 RNP to GLS Demonstration Planning

In October 2015, the team consisting of United Airlines, Delta Air Lines, Southwest Airlines and Boeing presented the RNP to GLS Demonstration proposal to SFO, SFO Tower, and Northern California (NORCAL) TRACON (NCT) facilities personnel. It was crucial to engage all stakeholders from the beginning of the demonstration planning. Stakeholders learned about RNP, GLS and GBAS, and their operational benefits. Next, the team collaboratively designed procedures to the affected runway ends to address specific operational constraints for SFO. Once procedure design was completed, the team planned and coordinated the demonstration activities. Such topics included RNP to GLS instrument approach procedures (IAPs), the required airspace coordination, procedure testing in the simulator and PBAS deployment.

The primary goal of the demonstration project planning team was to identify applications of RNP to GLS to improve overall operational dependability for the airport and airlines. For the airlines, operational dependability is defined as a schedule execution metric that addresses the on-time arrival/departure performance. For the airport, operational dependability is an efficiency measure that quantifies delays imposed by capacity constraints. For example using only runway 28R for arrivals below CAT I minima (200 feet ceiling and 0.5 sm visibility).

The demonstration effort relied on the day-to-day operational experience of the airlines at SFO and a complete assessment of the current air traffic operations. Since runways 28L and 28R are used for 94% of arrivals, and the simultaneous arrival operations are most affected by marginal weather, the team designed RNP to GLS IAPs for the SOIA and CSPO operational concepts to increase efficiency in these weather conditions. In addition, RNP to GLS procedures for runways 10L and 19R were designed to improve airport access by adding precision guidance to these seldom used runways.

## 3.1 Instrument Approach Procedures (IAP) Development and Testing

The goal of the San Francisco project was to develop concept IAPs as concept feasibility studies to demonstrate the capabilities of RNP and GLS to alleviate certain operational constraints at airports. Table 3 summarizes the design objectives for the RNP to GLS procedures for SFO.

*Table 3: SFO RNP to GLS IAP Design Objectives*

| | |
|---|---|
| **10L** | Add precision approach capability where none exists today and enable improved access during reduced weather minima. |
| **19R** | Add precision approach capability where none exists today without conflicting with the Oakland International Airport (KOAK) and enable improved access during reduced weather minima and do so with a continuous descent approach reducing fuel burn, carbon emissions and noise. |
| **28R** | Provide additional flight deck automation to enable simultaneous parallel operations and increase efficiency for certain aircraft pairs by potentially reducing aircraft spacing.<br><br>Reduce SOIA minima through use of airplane automation to mitigate pilot manual flight to runway alignment.<br><br>Provide a mitigation of wake effect on the CSPO by introducing incremental vertical separation between the ILS 28L and the GLS approach to 28R. |

All RNP to GLS IAP designs incorporate RNAV RNP 0.15 nm intermediate segments terminating in a GLS final. Intermediate segments serve to ensure a seamless transition between the RNP and GLS modes. The use of RNP AR (RNP with Authorization Required[10]) level navigation capability also supports safety case risk mitigation applications. In addition, the IAP designs utilize radius to fix (RF) Legs to link with the respective final approach point (FAP) for each runway.

The team used existing precision and non-precision approach procedures as the baseline for the new RNP to GLS procedures. Procedures were designed to interface with the existing airspace environment (e.g., beginning at the termination of published Standard Terminal Arrival Route (STAR)) and to enhance airport operations today. The table below summarizes the STAR feeder transitions in the airspace.

*Table 4: SFO STAR Connections & Transitions*

| Today's IAPs | GLS IAPs | STAR Connections & Transitions |
|---|---|---|
| **Localizer Type Directional Aid (LDA) 28R** | 28R W<br>28R V | East: DYAMD STAR<br>Southwest: SERFR STAR<br>North/Northwest: BDEGA TWO ARRIVAL (via CORKK) |
| **RNAV (GPS) 10L** | 10L P | North/Northwest: POINT REYES TWO ARRIVAL & STINS THREE ARRIVALS |
| **19L/19R** | 19R R | South: WWAVS ONE ARRIVAL & STLER TWO ARRIVA |

Jeppesen, a wholly owned Boeing subsidiary, supplied the approach plates. Procedures were designed to leverage the flexibility of RNP to GLS procedures including use of radius-to-fix (RF) turns, using RNP precision and containment to move noise over less populated areas including waterways, increased glideslope angles on final approach and displaced landing thresholds (also called alternate or secondary touchdown points). Due to the runway configuration, unique ceiling and visibility conditions, obstacle constraints and heavy traffic flow, each RNP to GLS procedure had a different design objective.

One specific operational note relates to the CORKK Transition only. Arming the localizer (LOC) and approach (APP) prior to completion of the RF Leg was not recommended due to possibility of capturing the LOC prematurely.

To fit in the existing airspace, the transition down the bay from CORKK was integrated into the IAP. Typical radar vectors from CORKK (north) are shown in Figure 6.

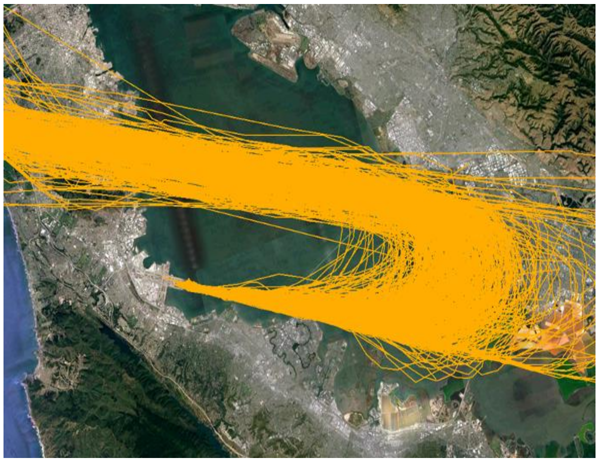


*Figure 6: Typical Radar Vectors from CORKK (North/Northwest) for Approach to 28R/L*

[10] RNP AR enables a higher level of navigation performance to better address issues of airport access, such as obstacle-rich environments, and facilitate advances in air traffic management (ATM), requires the operator to meet additional aircraft and aircrew requirements and obtain operational authorization from the State regulatory authority (Source ICAO http://www.icao.int/Meetings/PBN-Symposium/Documents/9905_cons_en.pdf )

### 3.1.1 GLS P RWY 10L

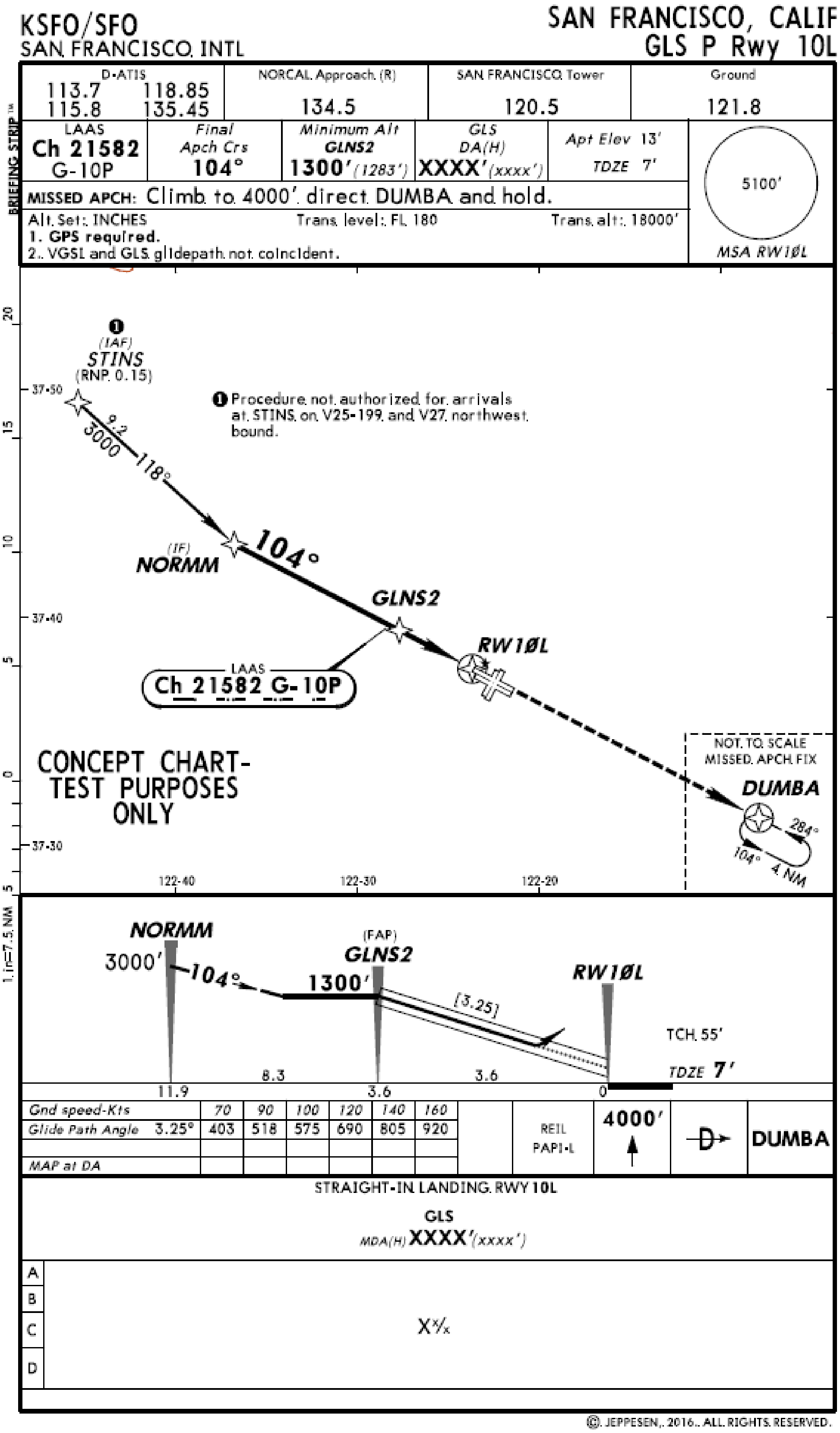



Figure 7: GLS P RWY 10L

Today, there is no precision approach to runway 10L. It is not possible to site an ILS due to the proximity to San Bruno Mountain and rising terrain close to the runway. As the final approach course passes through this terrain, the approach minima are high. The only approaches to these runways are visual and only in use when the winds and weather are unfavorable for other runways (less than 1% annually).

The first step to define the RNP to GLS procedure was to identify the obstacle field. The obstacle field Terminal Instrument Procedures (TERPS) criteria is shown in Figure 8. As a result, the existing procedure to 10L has 1200 feet Minimum Descent Altitude (MDA(H)) which requires a 4 nm final segment. The approach to runway 10L overlays a residential area with obstacles (including a hill, housing, light poles). GLS 10L P is an overlay of the existing charted RNAV (GPS) 10L and is served by the same STAR structure.

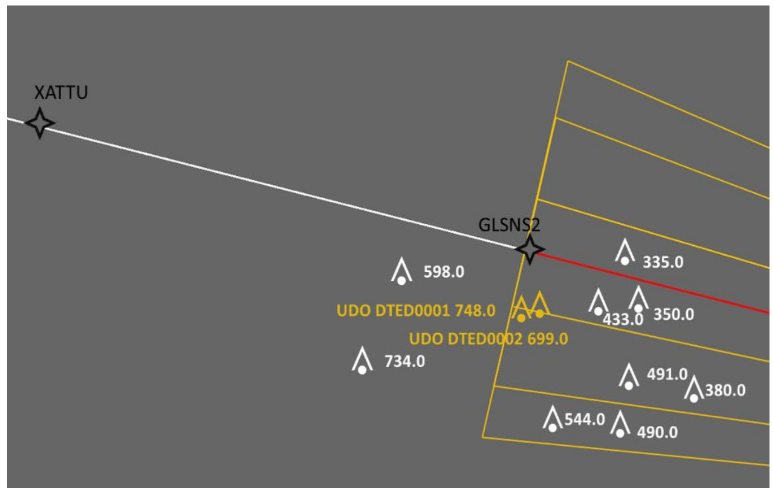


*Figure 8: 10L Obstacle Field (TARGETS)*

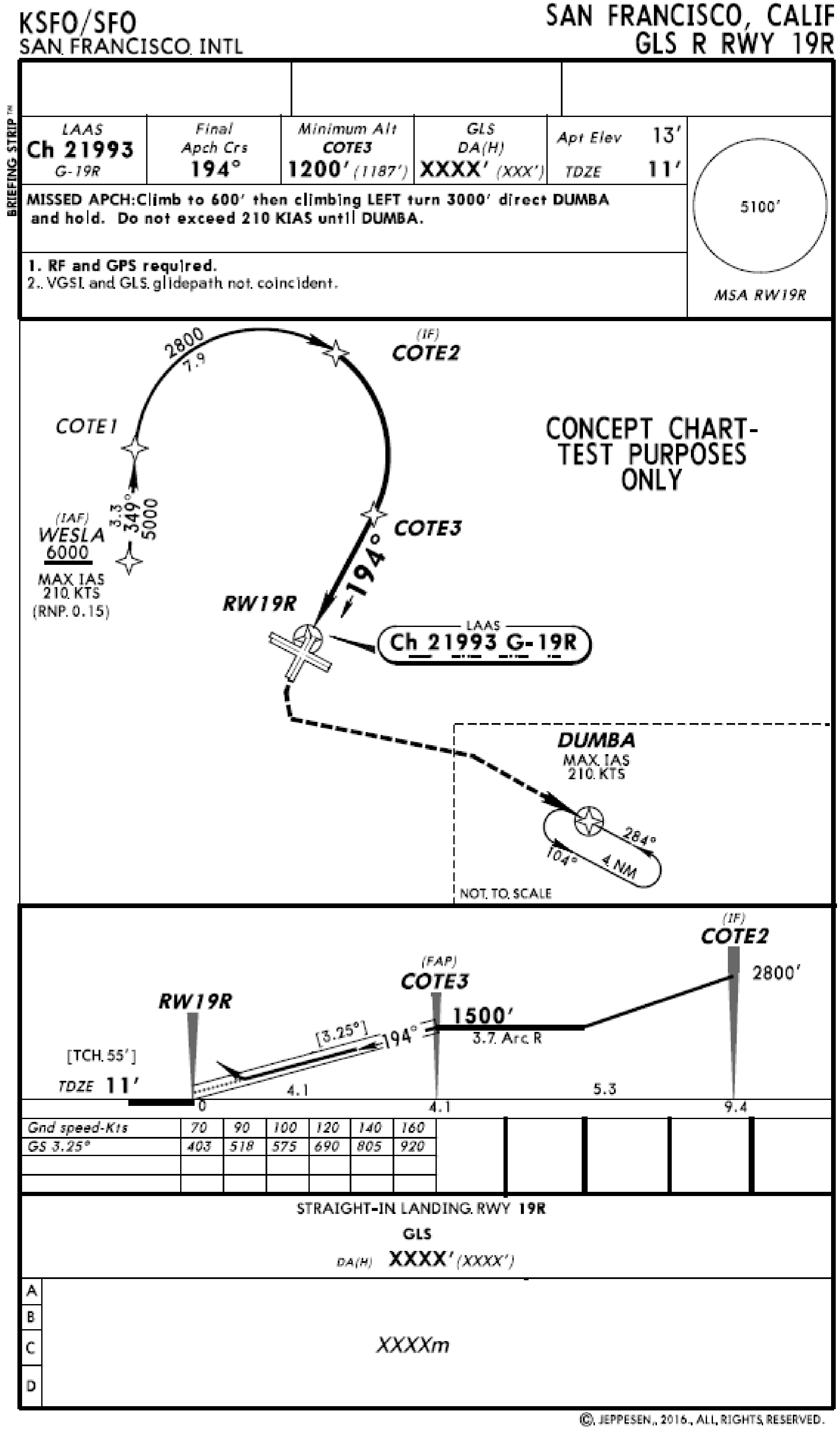
The team identified the points DTED0001 and DTED0002 (shown in yellow text in Figure 8) to be the controlling obstacles to be addressed in order to establish the glideslope. The two identified obstacles are “Adverse Assumption Obstacles” listed with an incremental 200 feet elevation assumption, meaning that the obstacle shown as 748 feet is actually 548 feet. Reassessment of these obstacles and a surveyed data set would enable the design of an optimal GLS glideslope.

For this demonstration procedure, a 3.25º glideslope was sufficient to clear the obstacle field. No effort was made to define controlling obstacles in terms of a MDA(H) or minima as the procedure was to be flown with visual reference to the runway as a prototype evaluation.

The simulation evaluation was confined to the existing transition to the GLS P 10L FAP with a 3.25º glideslope. Flight operational evaluation of the 3.25º glideslope resulted in a determination of no flight operational issues being identified.

The overall conclusion is that a GLS final segment on runway 10L is feasible, based on re-assessment of the two obstacles identified above. However, determination of DA(H) associated with the potential IAP design was beyond the scope of the demonstration effort.

### 3.1.2 GLS R RWY 19R




| Gnd speed-Kts | 70 | 90 | 100 | 120 | 140 | 160 |
|---|---|---|---|---|---|---|
| GS 3.25° | 403 | 518 | 575 | 690 | 805 | 920 |

*Figure 9: GLS R RWY 19R*

The approach to 19R was designed with multiple objectives: 1) add precision approach minima for runway 19R 2) connect the IAP to the existing STAR procedures from the south/southeast 3) maintain adequate separation from nearby OAK airspace and 4) demonstrate a low noise, fuel burn, and emissions approach.

The track begins at WESLA (6000 feet and 210 knots) and ends with a FAP 4.1 nm from the runway threshold. This short final is due to an air traffic control constraint associated with the Oakland runway 12 final approach. The OAK ILS RWY 12 final approach fix is at 1800 feet which requires 1000 feet vertical separation from the 19R track. As a result, the GLS R 19R approach has an altitude constraint of 2800 feet at COTE2.

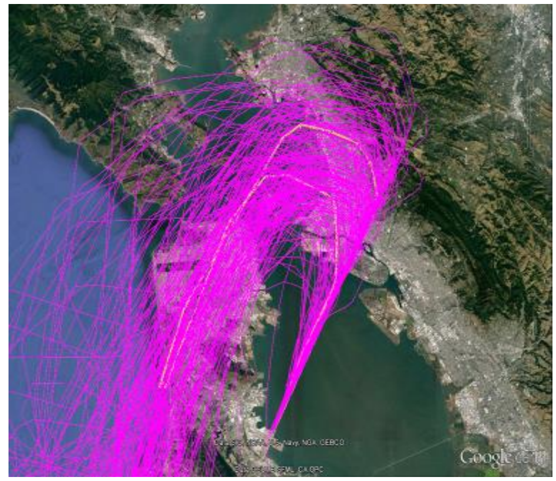


*Figure 10: Typical Radar Vectors from STLER TWO for Approach to 19L/19R*

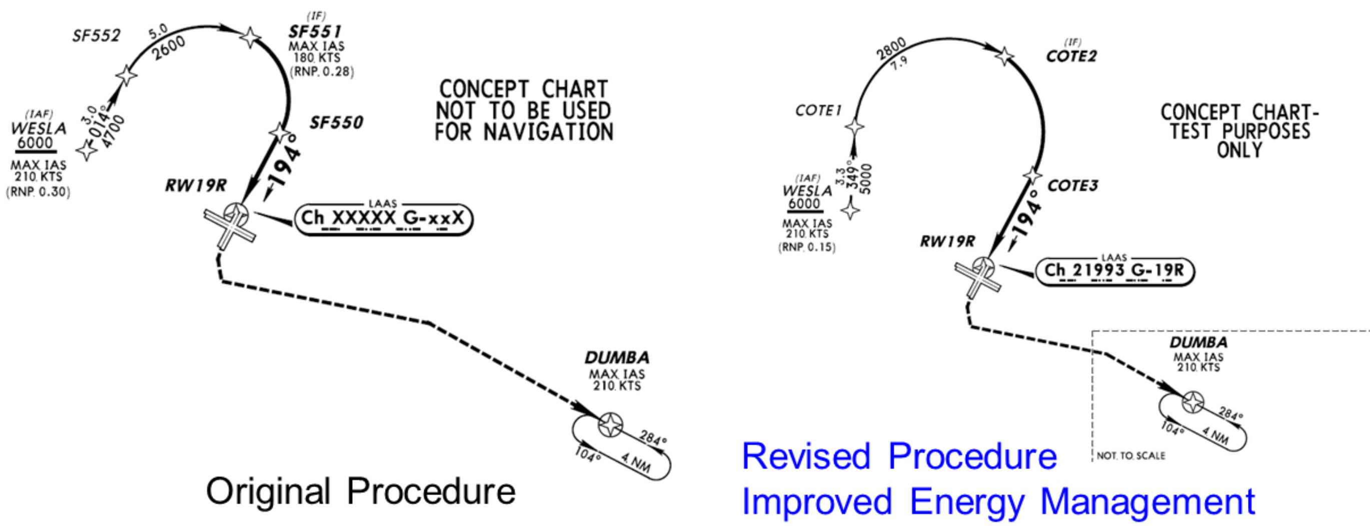



*Figure 11: 19R Procedures Revisions to Improve Energy Management*

In the first simulation session, the original procedure was deemed unacceptable from an energy management perspective because speedbrakes and premature configuration changes were required to control speed. In addition, the approach exhibited an excessive descent gradient to the FAP due to the 16 nm track distance. The objective of low energy approaches is to minimize the use of additional drag (e.g., speedbrakes, additional flaps or configuring landing gear early). Based on this finding, and in order to provide sufficient deceleration, the track distance was extended to 21 nm. While it may seem counter intuitive, the optimum descent path that results in a power-off, continuous descent without requiring premature configuration changes, may require more track distance yet still reduces fuel. The resulting GLS R RWY 19R procedure, as shown in the right on Figure 11, has improved energy management and increased pilot acceptability.

The GLS R 19R procedure z San Francisco. Noise and Emissions analysis for the 19R GLS R approach is discussed in Section 5.

### 3.1.3 GLS W RWY 28R– SOIA

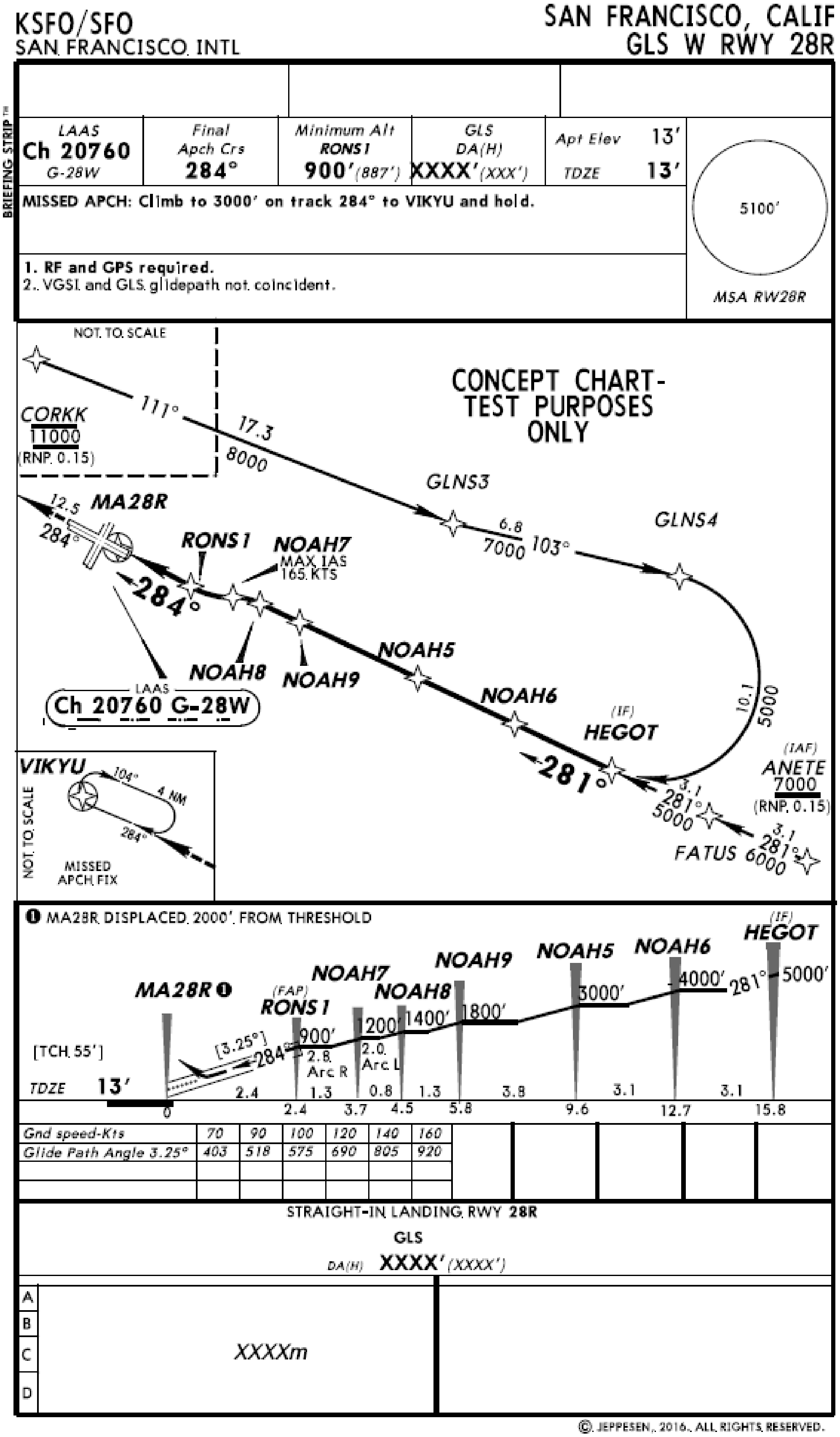



*Figure 12: GLS W RWY 28R*

The GLS W RWY 28R procedure was designed to enhance the SOIA to 28R in terms of reducing the weather minima compared to the existing localizer type direction aid (LDA) 28R IAP of 1600 feet. The GLS W approach began as near-parallel overlay of the existing LDA 28R ground track. However, there are two key differences between the existing LDA procedure and the GLS W approach.

Firstly, the point NOAH 7 is laterally offset 2500 feet from the 28L localizer (LOC) course– in the existing procedure, the point DARNE which is defined as the decision point to continue the 28R LDA approach visually is laterally offset 3000 feet from the 28L LOC course as shown in Figure 13.

Secondly, the GLS W approach design supports the use of autoflight capability through to the minimum disconnect altitude. This procedure supports use of flight automation during the SOIA operation – maintaining both vertical and lateral guidance all the way to the runway end. Note: DARNE is shown for reference only and is not included in the GLS W 28R design.

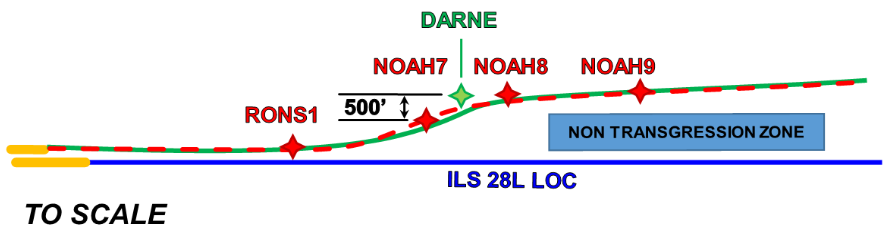



*Figure 13: Comparison of Existing ILS 28R and GLS W 28R*

The design features a transition from a Track to Fix (TF) to RF leg to shift the track toward the runway 28R LOC intercept. The RF leg allows the aircraft to maneuver from an offset position to LOC alignment without exceeding maximum bank angles for passenger comfort (12º-15º). The GLS LOC capture point was demonstrated immediately after NOAH7 typically 1000 feet laterally from the LOC centerline. LOC and glideslope (GS) capture was assured prior to crossing the FAP. The final GLS segment is 3.25$^0$ with a 2000 foot displaced threshold.

The 2000 foot displaced threshold with a 3.25º glideslope for the GLS W approach yields additional vertical separation between parallel abeam traffic (flying the 28L ILS) as summarized by Table 5.

*Table 5: Vertical Component Analysis ILS 28L and GLS W 28R*

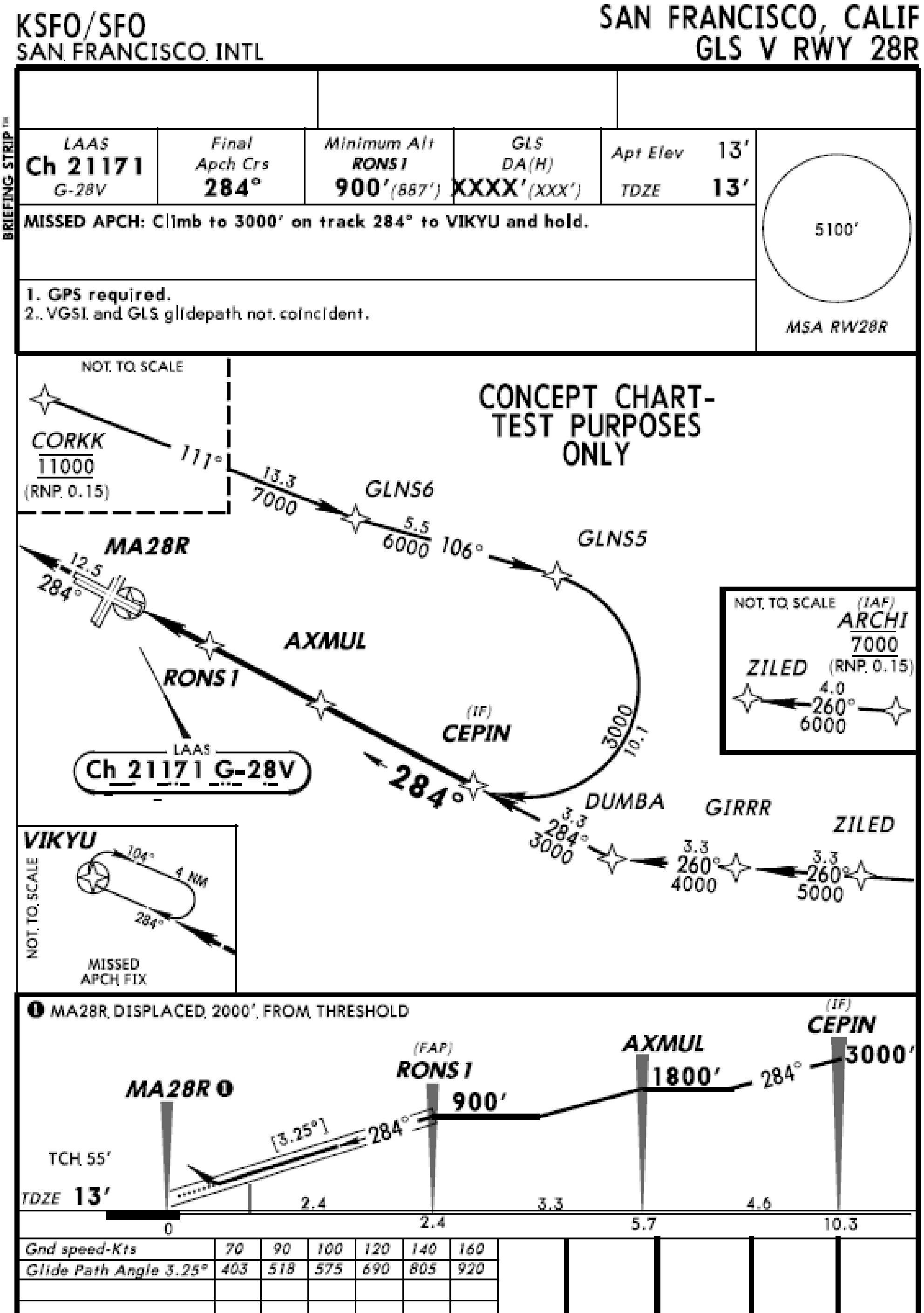
| Location / Waypoint | Height ∆ 28L ILS and 28R GLS W | Waypoint Descriptions |
|---|---|---|
| **NOAH7** | +290 feet | Transition/ Intermediate Step-Down |
| **RONS1** | +240 feet | Final Approach Point |
| **28L Threshold** | +155 feet | Abeam 28L Threshold |

This additional vertical separation represents a SOIA safety case enhancement for the GLS W RWY 28R approach. The intermediate segments were designed and coded as RNP 0.15 nm performance. This value of RNP may be applied to separation from traffic on 28L. The lateral track accuracy has been certified to a 95% level of RNP 0.11 nm (737NG without navigation performance scales) and the actual aircraft tracking performance meets or exceeds that specification. The accuracy of the lateral track guidance assures the LOC capture without risk of overshoot (See Appendix D – AFDS Performance GLS W 28R).

In addition, the human factors aspect of added vertical separation should be explored from a pilot workload management perspective.

### 3.1.4 GLS V RWY 28R – CSPO




| Gnd speed-Kts | 70 | 90 | 100 | 120 | 140 | 160 |
|---|---|---|---|---|---|---|
| Glide Path Angle 3.25° | 403 | 518 | 575 | 690 | 805 | 920 |

STRAIGHT-IN LANDING RWY 28R

GLS

DA(H) XXXX′(XXXX′)

| | |
|---|---|
| A | |
| B | |
| C | XXXXm |
| D | |

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*Figure 14: GLS V RWY 28R*

This procedure was designed to enhance the CSPO to runways 28L and 28R by adding vertical separation between the flight tracks for wake vortex mitigation. The GLS V approach began as an overlay of the 28R ILS procedure to runway 28R. At the request of NCT, the transition down the bay from CORKK was integrated into the IAP. One objective of this demonstration was to use RNP to GLS procedures to mitigate wake turbulence by increasing the vertical separation between the aircraft flying CSPO to runways 28L and 28R. Autoflight may be maintained throughout the procedure to minimum disconnect altitude.

*Table 6: Vertical Component Analysis ILS 28L and GLS V RWY 28R*

| Location / Waypoint | Height ∆ 28L ILS and GLS V RWY 28R | Decision Point Descriptions |
|---|---|---|
| **CEPIN** | +417 feet | GLS V Initial Fix (IF)<br>(Turn on at 10.5 nm) |
| **AXMUL** | +398 feet | GLS V FAP |
| **28L Threshold** | +155 feet | Abeam 28L Threshold |

Vertical separation was enhanced by implementing a 2000 foot displaced threshold and a 3.25º glideslope to the GLS V approach. The added vertical separation represents a safety case enhancement to be credited to the GLS V design path attributes. As shown in Table 6, the difference in flight path construction provides a significant geometrical height advantage between the approaches to runway 28L and 28R to be considered with wake turbulence issues.

The objective of the GLS V approach was to gain sufficient vertical separation to mitigate the wake of a heavy/B757 from the lead airplane on the left. FAA recommended in AC 90-23G pilots land long to avoid wake impact of heavy traffic on the parallel runway[11]. This procedure provides a precision approach to a long landing (in this report called a displaced threshold). For this analysis, consider the isolated pair of aircraft flying CSPO approaches to 28L and 28R (750 feet runway spacing). Note that this analysis does not address the complete 7110.308A operation as analysis trailing traffic is assumed well beyond the limits contained in the Order. The following is one suggested approach for comparing three cases;

1. CSPO with 2.85º glideslope to 28L and a 3.0º glideslope to 28R ILS with 1.0 nm spacing for a pair of airplanes consisting of a heavy/757 on 28R, and a large (737) on 28L

2. CSPO with 2.85º glideslope to 28L and a 3.25º glideslope with 2000 foot displaced threshold GLS V 28R with 1.0 nm spacing. This pair of airplanes consists of a heavy/757 on 28R, and a large (737) on 28L in the lead

3. CSPO with 2.85º glideslope to 28L and a 3.25º glideslope with 2000 foot displaced threshold GLS V 28R with 1.0 nm spacing (this reflects the proposed rule change reducing the spacing from 1.5 nm). The pair consists of a large (737) on 28R, and a heavy/757 (737) on the 28L in the lead.

Case 1 is the baseline case of CSPO operations once the proposed rule change to FAA Order 7110.308A is implemented. Case 2 is the baseline case for new GLS approaches to 28R. There is no change to the sorting of the aircraft. This proposed change reduces the required diagonal spacing from 1.5 nm to 1.0 nm. This rule is expected to be implemented in 2018. Further analysis is necessary to determine the safety case for removal of the restriction to airplanes flying in the lead (to 28L) during CSPO operations. The human factors aspects of added vertical separation should be explored from a pilot workload perspective.

[11] http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_90-23G.pdf

## 3.2 Boeing Simulation Sessions

Simulation sessions in the Boeing 737 NG Engineering Cab (also known as eCab) were completed with airline pilots from United and Delta, Boeing pilots, NCT, airport, engineering, and procedure designers. These sessions provided valuable information about the concept of operations including the flyability of the RNP to GLS procedures and provided an overview of the operations to all stakeholders including the airport and NCT.

The Boeing 737 NG eCab flight deck configuration is the same as current production Boeing 737 NGs. The Boeing 737 NG eCab included FMC U10.8A. The team evaluated procedures over a range of winds and temperatures. In addition, data from the Boeing 737 NG eCab sessions were used for environmental performance assessment. Aircraft parameters including aircraft configuration, fuel flow, net corrected engine thrust, pitch angles and altitudes were used to complete a preliminary assessment for community noise and fuel burn. Quantitative and qualitative data were collected during/after the simulations from the pilots and observers for each session. An image from the simulation session is shown in Figure 15.


*Figure 15: Boeing 737 NG eCab GLS W 28R Approach*

For initial evaluation, the IAPs were coded in a navigation database (NDB) and flown in a Boeing 737 NG eCab with Boeing pilots. After confirmation of fly-ability and aircraft systems performance was established, airline pilot personal were invited to fly the IAP and make input into the design process. The airline flight operational evaluation confirmed procedure design objectives were being met. Airline standard operating procedures (SOP) were utilized without any issues. Several iterations of the IAPs were completed based on feedback from the simulation sessions. The simulation sessions are summarized in Table 7.

*Table 7: Boeing 737 NG eCab Simulation Session Summary*

| Date | Attendees | Procedures and Description | Comments/ Summary/ Notes |
|---|---|---|---|
| **8-Dec-15** | Boeing | • 1st Chart Set<br>• Concept track based on overlays of existing IAP<br>• 28R SOIA, 28R CSPO, 19R and 10L | • No intermediate RF segments |
| **24/25-Feb-16** | Delta, United, Boeing | • 2nd Chart Set<br>• Full Jeppesen procedures<br>• 19R – Drag required to maintain speed and path | • Revised SOIA track to increase lateral separation<br>• 19R – Need to add extra track miles |
| **4/5-May-16** | Delta, Boeing | • 3rd Chart Set<br>• GLS Idents changed<br>• GLS channel numbers added | • Flew the DAL SOP<br>• Collected data for noise and emissions assessment |
| **27-Jun-16** | NCT, Boeing | • 3rd Chart Set | • Completed GLS autolands |

 

## 3.3 Portable GBAS Overview and Flight Check

### 3.3.1 Portable GBAS System Overview

Boeing provided a Portable GBAS (PBAS) to generate the GLS approach guidance. The PBAS transmits a GLS signal providing Type 1/2/4 messages per ICAO Annex 10 and DO-246. The PBAS equipment consists of a broadcast antenna, GPS reference receivers, a differential correction processor, and an operator interface. The equipment, displayed at Boeing Field prior to the demonstration, is shown in Figure 16.

The PBAS location was selected such that there was a clear line of sight to each runway end. The location of the PBAS is shown in Figure 17.

*Figure 16: PBAS Antenna, Transmitter, GPS Receivers, Power Supply*

### 3.3.2 Flight Check

To validate the approach procedures, and verify no design changes were required, a flight check of the instrument approach procedures was conducted on August 6th, 2016. Boeing utilized a flight test instrumented 737-8 MAX. Figure 18 shows the aircraft on the runway in SFO.

Prior to takeoff from SFO, all four of the GLS channels were selected to verify proper tuning. Relevant parameters, such as distance-to-threshold (DTT) and localizer deviations, were evaluated from the flight deck. Autopilot coupled GLS approaches were then conducted to runway 28R using the GLS W and GLS V procedures. The approaches terminated with an automatic go-around at 50 feet AGL on the first approach and a full stop landing from 50 feet AGL on the second approach. Both approach procedures were flown from the beginning of the intermediate approach segment to the GLS final.

Low ceilings to the north and west of the airport prevented execution of the 10L and 19R approach procedures. The overall results were excellent and the aircraft tracked both the lateral and vertical flight paths with sub-meter precision.


*Figure 17: PBAS Location*


*Figure 18: 737-8 MAX at SFO for GLS Flight Check*

# 4 Flight Demonstration on August 27th, 2016

Significant coordination and pre-planning was required for the success of this demonstration. The date and time of the demonstration was agreed upon for several reasons:

1. Ceiling and visibility conditions were most likely (based on historical data) to be the most favorable to all runway ends in the August/September timeframe. The team was concerned with the ceiling and visibility during the demonstration because it was a requirement to maintain VMC.

2. Airlines would have more aircraft availability in San Francisco prior the Labor Day rush (aircraft are moved to other locations for other routes post Labor Day).

3. Early evening was seen as the ideal time because of typically lower traffic volumes at SFO.

Since two of the four procedures were opposite the typical flow of traffic (which is landing to runway 28L/28R and taking off from runway 01L/ 01R), much care was taken to properly sequence the two demonstration aircraft while maintaining normal traffic flow for the remainder of the Bay Area.

Both Delta Air Lines and United Airlines provided aircraft and participated in the demonstration flights. Delta Flight 9984 was a Boeing 737-900ER and United Flight 2183 was a Boeing 737-900ER. Custom NDBs with the demonstration RNP to GLS procedures were loaded onto the aircraft after completion of scheduled revenue service on August 27th, 2016. The NDBs were verified in both aircraft once the pilots arrived onboard.

The PBAS was setup in the early afternoon of August 27th, 2016 and started broadcasting immediately (Figure 19). PBAS guidance was verified prior to departure for the demonstration flights. The pilots verified all four GLS procedures and verified proper decoding of the approach information – approach identification, course runway and a reasonable distance to threshold – on the primary flight display (PFD).

The team built the demonstration sequence to maximize the probability of VMC to complete all of the approaches. The full flight sequence is show in Appendix A– 27-Aug-16 Flight Sequence.

*Figure 19: United 2138, Delta 9984 and the PBAS (GPS Antenna Visible)*

## 4.1 GLS P RWY 10L

The first approach set in the sequence was 10L with the United 2138 flying first, and Delta 9984 flying second[12]. Both aircraft started the IAP at the waypoint STINS, and shortly after engaged localizer and glideslope around 3000 feet - 3400 feet. Due to the marine layer at around 1000 feet, both crews leveled off, and completed go-arounds in order to maintain VMC as seen in Figure 20.

United 2138 commenced the go-around at 2000 feet and Delta 9984 commenced the go-around at 1000 feet radio altitude (RA). Despite not being able to complete the approach down to 100 feet RA, the approach was deemed successful because both crews indicated that lateral and vertical GLS guidance appeared accurate and aligned with the runway.

*Figure 20: SFO during 10L Approach*

## 4.2 GLS R RWY 19R

The second approach in the sequence was to runway 19R.  Delta 9984 was the lead airplane, and United 2138 in trail. Figure 21 shows United 2138 just prior to go-around. Both aircraft started the IAP at the waypoint WESLA following the charted speeds. Localizer and glideslope engaged as planned around 3000 feet and both crews completed a go-around from 100 feet RA. Both aircraft were able to fly the procedure without speedbrakes and reported a smooth transition from the RNP to GLS with a good idle descent.

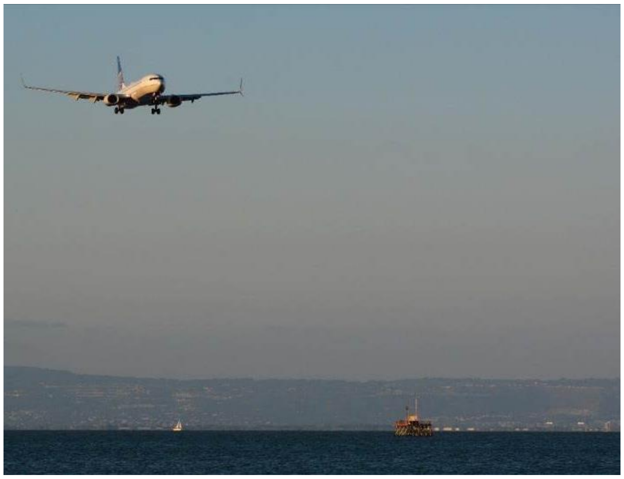

*Figure 21: United 2183 on GLS R 19R Approach Prior to Go-Around*

## 4.3 Baseline Approach ILS 28R

A baseline 3º ILS approach to runway 28R was completed to provide a comparison for pilot feedback and reactions regarding the displaced threshold, the increased glideslope, idle power setting and flap settings.

[12] This was a change to the sequence – due to SFO gate locations, United 2138 started taxiing to runway 28R for departure before Delta 9984 and subsequently was first to takeoff and enter the demo sequence

## 4.4 SOIA – ILS RWY 28L and GLS W RWY 28R

Two pairs of SOIA approaches were completed. NCT successfully sequenced both aircraft into the pattern to complete the simultaneous approach. The first featured United 2138 flying the GLS W approach, and Delta 9984 was vectored to ILS 28L as shown in Figure 22. Note the large vertical separation between Delta 9984 and United 2138. United 2138 flew the full IAP starting at the waypoint CORKK. Localizer and glideslope engaged at the waypoint HEGOT at approximately 5000 feet as expected.

The second SOIA approach included Delta 9984 flying the GLS W and United 2138 was vectored to ILS 28L. Delta 9984 flew the full IAP starting at waypoint CORKK. Localizer and glideslope was engaged as expected inside waypoint HEGOT. Unfortunately, United 2138 experienced a deliberate aiming of a handheld green laser into the flight deck, and the flight crew recovered to complete the approach safely.

*Figure 22: Delta 9984 flying ILS 28R (foreground) and United 2183 flying GLS W 28R*

The SOIA approach features two RF turns immediately prior to the FAP, RONS1 which is located 2.9 nm from the displaced runway threshold. Data recorded from the aircraft were used to assess the mode transitions: lateral from LNAV to localizer and vertical from VNAV to glideslope as shown in Figure 23. Aircraft systems (AFDS) performance for one representative approach is shown in Appendix D – AFDS Performance GLS W 28R*.* The VNAV PATH (which is the RNP portion of the approach) to the GLS glideslope transition was demonstrated to be operationally acceptable for the ambient conditions experienced during the flight.

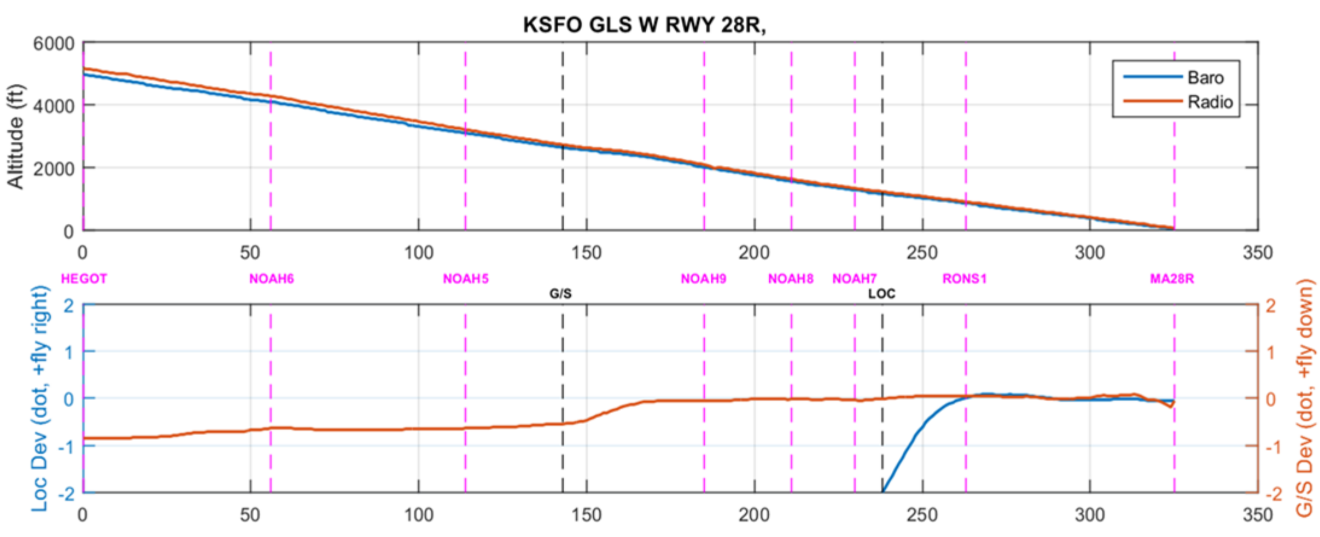


*Figure 23: GLS W 28R AFDS Performance*

 

## 4.5 CSPO – ILS RWY 28L and GLS V RWY 28R

Figure 24: View of Delta 9984 from United 2183 in the CSPO Approach

Two pairs of CSPO approaches were completed. NCT sequenced both aircraft into the pattern to allow for simultaneous approaches to the ILS on runway 28L and the GLS V on 28R. The first features United 2138 flying the GLS V approach, and Delta 9984 flying the ILS. United 2138 started the approach from CORKK at 10000 feet[13]. The approach was armed during the RF turn, and localizer and glideslope engaged at CEPIN.

The second CSPO approach included Delta 9984 flying the GLS V and United 2138 flying the ILS approach to runway 28L. Delta 9984 started the approach at CORKK at 11000 feet. Approach was armed inside waypoint CEPIN, localizer and glideslope engaged shortly after. In Figure 24, Delta 9984 is visible from the starboard side of United 2138.

Delta 9984 terminated the approach in a full stop landing. United 2138 commenced a go-around due to another aircraft on the runway. In addition, United 2138 experienced interference on the ILS beam resulting in an aggressive pitch and level off maneuver. Aircraft data was used to assess the mode transitions: lateral from LNAV to localizer and vertical from VNAV to glideslope See Appendix E for plots of the airplane performance.


Figure 25: View from Delta 9984 flight deck on GLS V 28R - Note the 4 White on the PAPI and the 2000' Displaced Threshold

[13] 10000' instead of 11000' as charted.

 

## 4.6 Summary of Demo Flights

In summary, Delta and United completed all conditions in the demo sequence (a total of 14 approaches) to validate the RNP to GLS procedures. Table 8 summarizes the flight.

*Table 8: Summary of Flight Demo*

| Runway | Flight Sequence | Summary |
|---|---|---|
| **10L** | United, Delta | Multichannel autopilot coupled<br>UAL go-around at 2000 feet & DAL go-around 1000 feet to maintain VMC |
| **19R** | Delta, United | Multichannel autopilot coupled<br>Successfully completed approaches to 100 feet RA go-around<br>“Exceeded expectations” |
| **28L/28R**<br>SOIA | Pair 1: DAL ILS, UAL GLS | Multichannel autopilot coupled UAL<br>Successfully completed the paired approach |
| | Pair 2: UAL ILS, DAL GLS | Multichannel autopilot coupled DAL<br>Successfully completed the paired approach |
| **28L/28R**<br>CSPO | Pair 1: DAL ILS, UAL GLS | Multichannel autopilot coupled UAL<br>Successfully completed the paired approach<br>Noticeable vertical separation |
| | Pair 2: UAL ILS, DAL GLS | Multichannel autopilot coupled DAL<br>Successfully completed the paired approach |

The actual flight tracks from August 27th, 2016 are shown in Figure 26 and Figure 27. Coordination and sequencing from NCT was phenomenal.

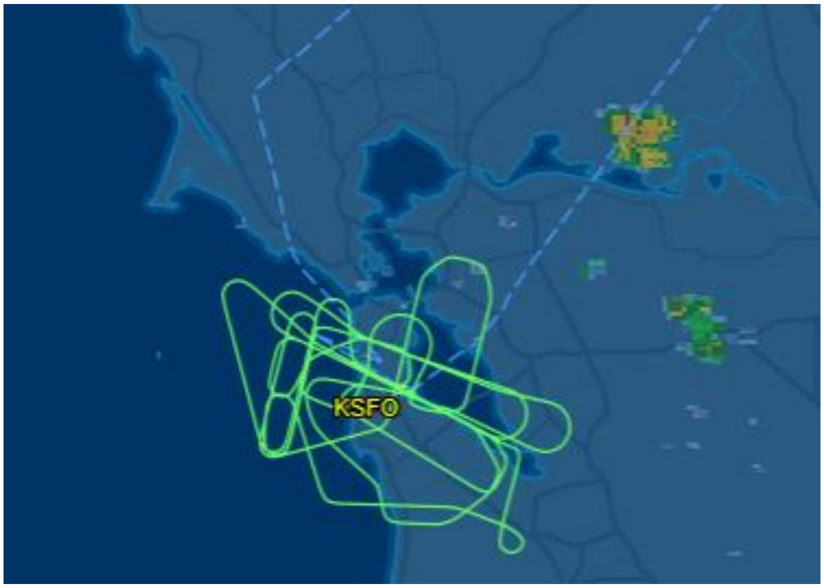


*Figure 26: DAL 9984 Flight Track Courtesy of FlightAware (flightaware.com)*

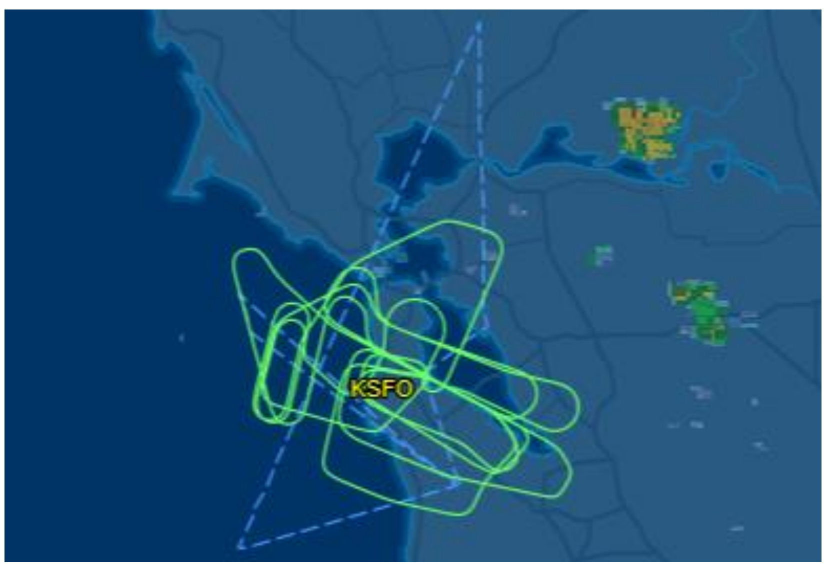


*Figure 27: UAL 2183 Flight Track Courtesy of FlightAware (flightaware.com)*

 

# 5 Environmental Performance Assessment

The environmental performance objectives of these RNP to GLS procedures are to increase flight efficiency, reduce fuel burn and carbon emissions, and lessen community noise exposure. Estimates for environmental performance were derived from engineering analyses and Boeing 737 NG eCab sessions. The estimates were validated with analyses derived from flight parameters recorded during the demonstration flights on August 27th, 2016.

## 5.1 Fuel Burn and Carbon Emissions GLS R 19R

Initial analysis was performed using computer-based performance software, Boeing Climbout Performance Tool (BCOP), to model approach performance over a range of aircraft configurations, concept flight tracks, thrust management profiles, weather conditions and other flight parameters.

For the analysis and route design of GLS R 19R, NCT provided approximately 260 radar vector routes into SFO runway 19L. Two typical baseline arrival tracks were identified, as shown in Figure 28; the typical long vector route (shown in blue) and the typical short vector route (shown in red). These two tracks were used for comparison with newly designed GLS R 19R procedure (green). All three of the routes track close proximity to waypoint WESLA at 6000 ft.

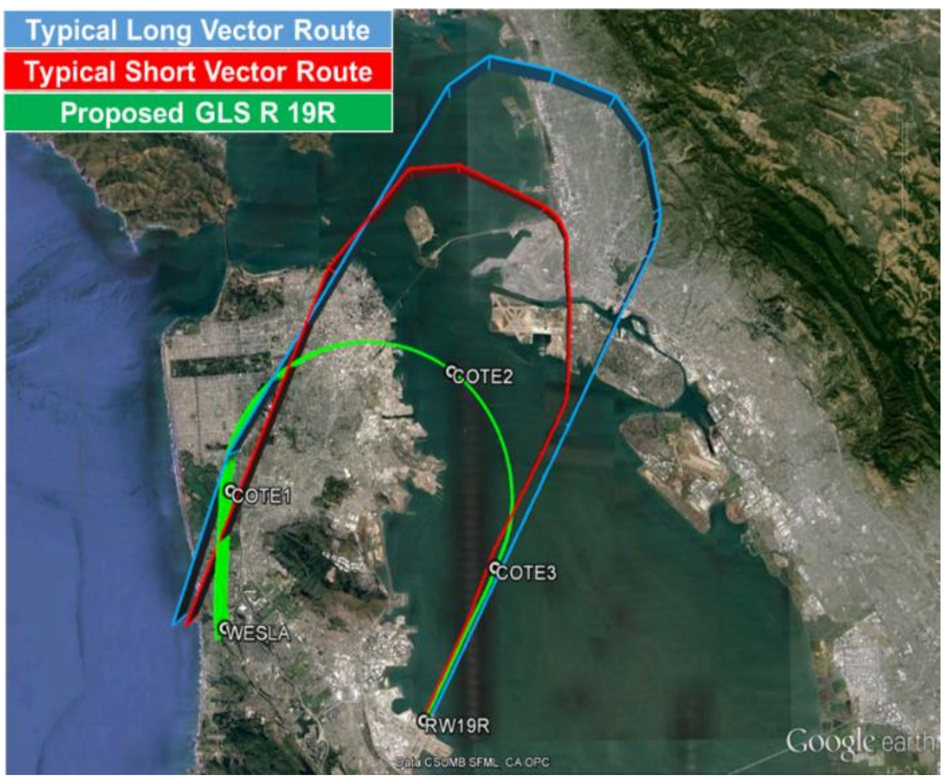


*Figure 28: Representative Routes to Runway 19L/ 19R*

Figure 29 shows the vertical track comparison between the typical short and long vector radar routes to runway 19L and the proposed (green) GLS R 19R. For fuel burn and emissions analysis, the selection of a common point to start the analysis is necessary to adequately compare results. The waypoint WESLA was selected as the common point to begin the analysis for fuel burn calculations. The vertical profiles for all three routes begin at the waypoint WESLA and end at the threshold to runway 19L/19R.

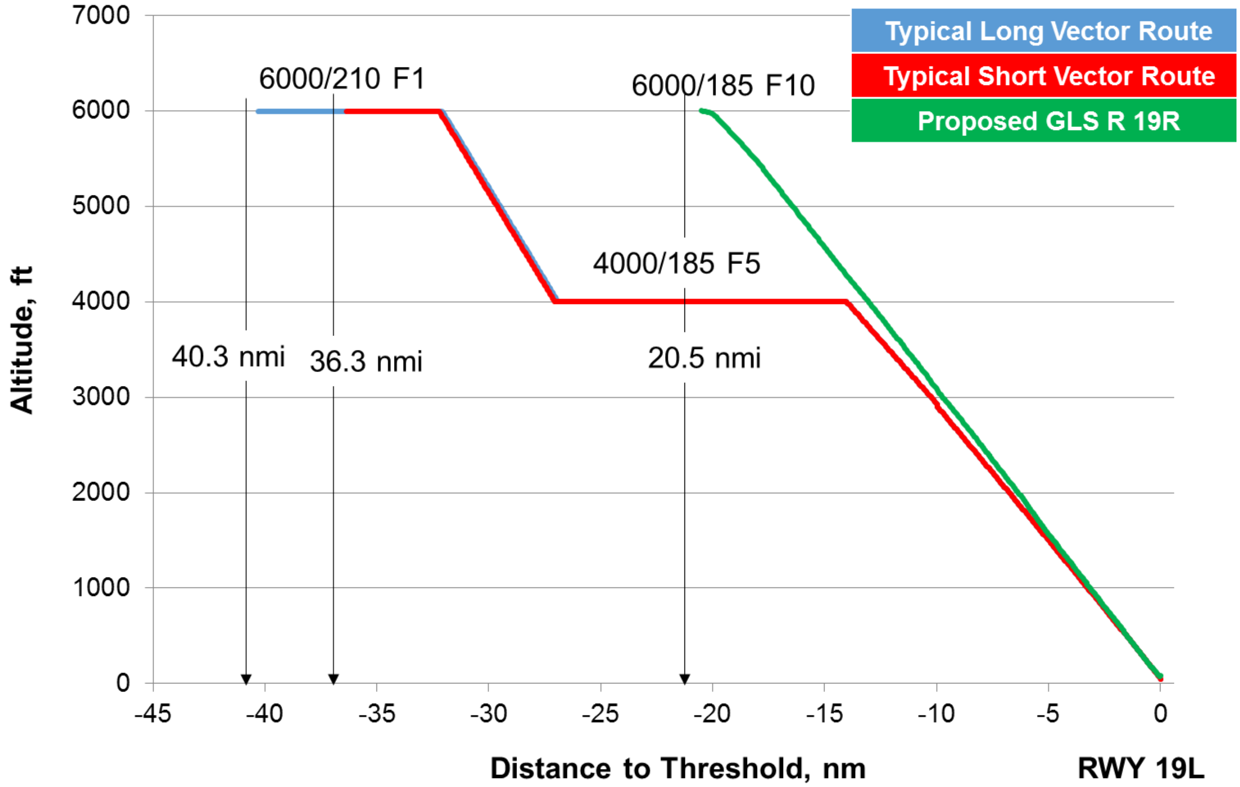


*Figure 29: Common Vertical Descent Point for 19R Analysis*

The GLS R 19R route features a continuous descent profile over 20.5 nm which provides a track distance reduction of 15.8 nm to 19.8 nm from the typical short and typical long vector routes. The estimated operational benefits derived from the computer-based analysis were validated during the Boeing 737 NG eCab sessions. During these simulation sessions in the Boeing 737 NG eCab, aircraft parameters including engine operations, fuel flow, and configuration were collected. This data provides higher fidelity aircraft performance estimates than computer based models alone, and introduces the human interface element of the pilot.

Table 9 summarizes the difference among the three tracks. The reduction in track length improves flight efficiency and results in a reduction of fuel burn and $CO_2$ emissions.

 

*Table 9: Distance, Fuel Burn and Emissions Comparison 19R - Simulator Performance*

| Arrival Route to 19R | Distance [nm] | Estimated Fuel Burn [lbs] | $CO_2$ Emissions [lbs] |
|---|---|---|---|
| **Long Vector** | 40.3 | 980 | 3092 |
| **Short Vector** | 36.3 | 792 | 2319 |
| **GLS R 19R** | 20.5 | 424 | 1338 |
| Savings with GLS R 19R compared to the Long Vector | **19.8 nm** | **556 lbs fuel** | **1754 lbs $CO_2$** |

## 5.2 Community Noise Assessment GLS R 19R

The population exposure to community noise was modeled using the FAA's Integrated Noise Model (INM).The noise contours from INM and population data from the US Census Bureau[14] was integrated using ArcGIS, a geographic information system used for mapping, and Google Earth.

The noise contours and population exposed for the three routes are compared in Figure 30. The typical short vector route exposes 329,600 people to the 55 dBA $LA_{MAX}$[15] contour, and the typical long vector route exposes 296,500 people to 55 dBA $LA_{MAX}$ contour. When the weather dictates landing on runways 19L and 19R, aircraft are vectored over the city of Oakland exposing many to noise. To accommodate the ILS on runway 19L, a long, straight in final segment is required. This straight final segment also causes interference with Oakland airport. The GLS 19R route reduces the population exposed to community noise by between 249,200-282,300 people. In addition, the flight track itself is much shorter and the final approach overflies the water.

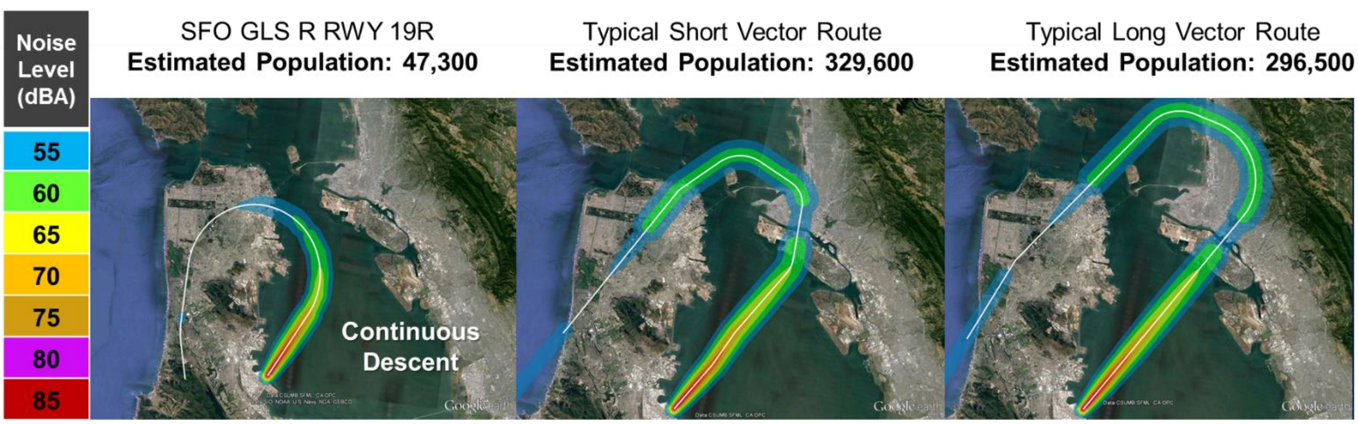


*Figure 30: Community Noise Exposure for Approaches to Runway 19L/19R*

[14] 2010 Topologically Integrated Geographic Encoding and Referencing (TIGER) data

[15] $LA_{MAX}$ shows the highest noise level reached in a given time period (http://www2.luton.gov.uk/NapierPark/PDFs/Environmental_Statement/Appendices/Noise_and_Vibration/NV1.pdf)

 

This reduction in community noise is due mostly to the avoidance of overflight of the densely populated Oakland region. In addition, the required thrust throughout the profile is less due to the low energy, continuous, near idle descent. Removing the 4000 feet level segment typical for this approach reduces the required thrust for the approach, the fuel burn and source noise at the aircraft.

The RNP to GLS approach to runway 19R was redesigned to improve the speed and altitude profile during descent. The objective of a low energy approach is to minimize the use of added drag (e.g., speedbrakes, configuring the landing gear early). Adding drag to decelerate increases the required thrust to stay aloft on speed and increases the community noise. The revised RNP to GLS procedures to 19R features an efficiency optimized profile that utilizes a near-continuous, idle-thrust descent to landing.

## 5.3 Demonstration Flight Data

The final validation of benefits for this project employed airline Flight Operations Quality Assurance (FOQA) Quick Access Recorder (QAR) data and airport provided flight tracks to quantify the operational and environmental benefits of RNP to GLS approach procedures.

### 5.3.1 Community Noise and Emissions for 19R

Data collected from the airlines were analyzed to determine the actual fuel burn during the approach to 19R was 327 lbs; the Boeing 737 NG eCab simulator performance predicted a fuel burn of 424 lbs. Differences in fuel burn are expected between actual flights and the simulator performance due to differences between the actual airplane and simulator configuration in flight (e.g., exact timing of flap schedule, differences in aerodynamic models, engine wear).

The SFO Noise Monitoring system is used to help the airport and communities manage and verify the airport noise footprint. To achieve this, the San Francisco Airport Commission has placed 29 permanent and placed four portable noise monitor terminals (NMT) in the communities surrounding the airport. Data from the system assists with identification of overall trends in noise levels, evaluating airline compliance with noise abatement flight tracks and provides a data source for following up on unusual occurrences. Using a correlation of radar tracks the airport has the capability of tracking flights and correlating them with noise levels registered at these NMTs.

For the RNP to GLS demonstration, the SFO Noise Abatement office correlated noise measurements with the two airline demonstration aircraft. Of interest to this study, both airplanes registered noise levels at NMT 25 during the approaches to 19R. Flight Tracks for United 2138 and Delta 9984 are shown as they initiated the GLS R 19R track in Figure 31. Both 737-900ER aircraft were measured at approximately 60 dBA $LA_{MAX}$. The INM analysis indicated the noise in this area would be less than 55 dBA. Differences between measured noise and analytical models can be due to differing ambient conditions (e.g., temperature, humidity, or winds) as well as pilot actions and airplane configuration.


*Figure 31: DAL and UAL Approaching 19R on SFO NMT*

The noise measurement shown at NMT 25 highlights a capability of the SFO airport to correlate flight tracks and noise events. The major environmental benefits of the RNP to GLS approach to 19R approach route are the shortened ground track that avoids overflight Oakland and a continuous descent, low energy, low drag profile. This flight path is a model for routes that can be used to reduce community noise, fuel burn and emissions.

 

*Table 10: Fuel, Emissions, and Noise Benefits of 19R GLS R Approach Procedure*

| Existing Procedure to Runway GLS R 19R | Delta Distance [nm] | Delta Fuel Burn [lbs] | Delta $CO_2$ Emissions [lbs] | Noise Exposure [people] |
|---|---|---|---|---|
| **Baseline Long Vector** | +19.8 | +556 | +1,754 | +249,200 |
| **Baseline Short Vector** | +15.8 | +368 | +981 | +282,300 |

### 5.3.2 Community Noise and Emissions for 28R

All the GLS final approach segments featured a 3.25º glideslope. A higher glideslope in the final approach segment can provide incremental fuel burn reduction over a typical 3.0º approach. During the flight sequence, a baseline approach to the 3.0º ILS to runway 28R was completed by both Delta and United. This baseline case was compared to the GLS V approach from an altitude of 3000 feet (near to the initial fix for the approach). Airplane performance data comparing the two approaches is provided in Figure 32. The top graph in the figure compares altitude versus track distance from the runway threshold. The bottom graph compares the rotational speed of the fan as a percent (Technical term is 'N1 #1 CMD') which is proportional to engine thrust versus the track distance from the runway threshold. Fuel flow rates are integrated over the approach to determine the total fuel burned during the approach.

The baseline approach to ILS 28R has two level segments, one at 4000 feet AGL and another 2000 feet AGL. The fuel burn reduction in the GLS V approach, and accompanying emissions reduction, is due to the absence of level segments.

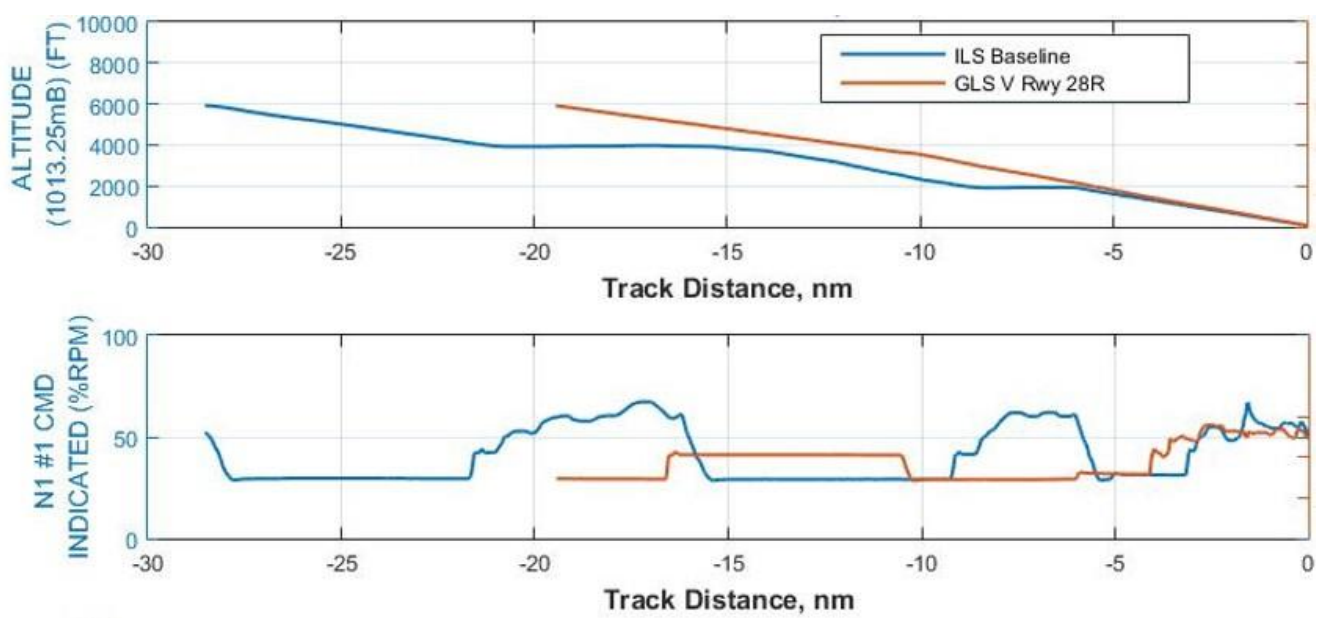


*Figure 32: Altitude and Engine Throttle Setting Comparisons for Approaches to 28R*

Data support an estimate of a fuel burn reduction of up to 50 lbs per approach (158 lbs carbon emissions) for well-designed RNP to GLS procedure with a 3.25º final approach glideslope. Previous analysis predicted fuel savings of up to 20 lbs for a 737NG. This flight represents one sample only. The data from any single flight can be influenced by many factors including pilot throttle movement, winds, and aircraft weights. While this value indicates a savings of 30 lbs more than an analytical estimate, it is within the range of fuel used given the variability.

 

It is important to note that simply adding a higher final approach segment to the existing lateral path by extending the level segment is insufficient to improve efficiency. With these newly designed RNP to GLS procedures, care was taken to modify the altitudes at existing waypoints and fixes to eliminate the need for level segments altogether.

Flight tracks for United 2138 and Delta 9984 are shown as they completed the SOIA paired approach to 28L/28R in Figure 33 at NMT 12 (Foster City, CA).

NMT 12 registered the noise level as each plane flew near the monitor. As seen in Figure 33, United 2138 was closer to the monitor approaching ILS 28L. United 2138 registered 0.5 dBA higher than Delta 9984. This result is as expected since Delta 9984 was further from the monitor. The SFO Noise Abatement Office encourages flight further away, laterally and vertically, from NMT 12 to reduce community noise for the Foster City Neighborhood.


*Figure 33: DAL and UAL CSPO Approach 28L/28R on SFO NMT 12*

 

# 6 Summary of Operational Benefits for RNP to GLS IAPs

Four RNP to GLS Instrument Approach Procedures were developed to support the SFO GLS demonstration. The enabling technologies are the 737NG's capability for both RNP 0.11 (AR) RF turn and GLS CAT I available on most Boeing production aircraft. Table 11 summarizes the objectives, technical features, and the Near and Mid Term benefits to San Francisco International Airport operations. The team believes these objectives can be achieved by building on the work done in this demonstration.

*Table 11: Objectives, Enablers, and Benefits for RNP to GLS Instrument Approach Procedures*

| | |
|---|---|
| **GLS P RWY 10L** | |
| **Objectives** | • To demonstrate aircraft automation driven flight procedures that provide accurate, precision 3D guidance on a terrain challenged approach<br>• To enable continuation of airport operations during periods when strong winds dictate use of runway 10L for arrival |
| **Procedure Characteristics** | • RNP 0.15 based RNP STAR transition with 3D guidance to capture GLS RWY 10L final approach<br>• 3.25º glideslope on final approach |
| **Near Term Operational Benefits** | • Near term possibility of an RNP AR procedure with improved minima |
| **Long Term Operational Benefits** | • Implement RNP 0.15 AR STAR transition to a GLS 10L final approach<br>• GLS approach minima would be near to CAT I to 10L<br>• Would enable the airport to continue to operate with fewer missed approaches than with existing RNAV approaches to 19L/19R |
| **GLS R RWY 19R** | |
| **Objectives** | • To demonstrate aircraft automation driven flight procedures that provide accurate, precision 3D guidance from downwind to decision height, and provide a more efficient, environmentally friendly flight path that is de-conflicted from Oakland Runway 12 approach traffic |
| **Procedure Characteristics** | • RNP 0.15 transition with 3D guidance based on an RF leg transition from downwind to capture GLS final approach path<br>• Runway 19R with a GLS final approach procedure<br>• Low energy approach with vertical profile that limits the use of added drag devices<br>• 3.25º glideslope on final approach |
| **Near Term Operational Benefits** | • Implement RNP 0.15 AR approach with an RF leg to Runway 19R to gain reduced track miles, noise reduction and fuel savings<br>• RNAV (RNP) RWY 19R minima should be near 400 feet |
| **Long Term Operational Benefits** | • Implement RNP established operations that utilize an RNP STAR from downwind, transitioning to a GLS 19R final approach<br>• GLS approach minima would be near to CAT I to 19R |

| GLS W RWY 28R | |
|---|---|
| **Objectives** | • To demonstrate aircraft automation driven flight procedures that provide accurate 3D guidance from a STAR that starts on downwind, transitions to an offset approach path<br>• RF guided turns to intercept the straight-in precision final approach segment of runway 28R<br>• Implementation supports enhanced safety case for offset parallel operations with aircraft on runway 28L |
| **Procedure Characteristics** | • RNP 0.15 STAR transition with 3D guidance initiated from the downwind, over the bay<br>TF leg transition to the offset course, followed to a point with 2500 feet lateral separation from the runway 28L final approach course<br>• Two RF leg turns that provide guidance to capture the 28R straight-in final approach course<br>• GLS final approach path, with a $3.25^0$ glideslope and 2000 foot displaced touchdown point. (Approach to Runway 28L was existing ILS with a $2.85^0$) |
| **Near Term** | • Implement RNP 0.15 STAR transition / IAP to provide 3D vertical guidance from downwind to completion of the RF leg S turns to line up with the final course supporting visual approach segment to 28R<br>• Use this procedure to gather data on flight track performance to develop the safety case to reduce the ceiling for SOIA (ex: 1200 feet, from current 1600 feet)<br>• Procedures will enable increased use of SOIA-like procedures with higher advertised arrival rate (AAR) during weather below visual minima |
| **Long Term Operational Benefits** | • Implement RNP established operations with an RNP STAR (RF transition) that incorporates the SOIA offset, and RNP RF transition to a GLS final approach with 2000 foot displaced threshold and $3.25^0$ glideslope<br>• The combination of 3D precision guidance to touch down, and displaced threshold and vertical separation could mitigate wake turbulence encounter risk, and a reduction of ceiling and visibility required to conduct SOIA |

| GLS V RWY 28R | |
|---|---|
| **Objectives** | • To demonstrate aircraft automation driven flight procedures that provide accurate 3D guidance from downwind to decision height/touchdown<br>• Key enabler for more closely spaced dependent operations to parallel runways 28R and 28L |
| **Procedure Characteristics** | • RNP 0.15 arrival with 3D guidance based on an RF leg transition from downwind to capture of the final approach path.<br>• Runway 28R with a GLS final approach with a 3.25º glideslope and 2000 foot displaced threshold, and 28L ILS with a 2.85º glideslope |
| **Near Term Operational Benefits** | • Implement RNP 0.15 STAR transition in concert with CSPO 1 nm stagger with target arrival rate increase from current 34 to 36 to potential 35 to 37 per hour |
| **Long Term Operational Benefits** | • With installation of a GBAS at SFO, implement RNP established operations to a GLS 2000 foot displaced threshold and 3.25º glideslope enabling a 0.6 nm stagger for CSPO, to gain a target arrival rate of potentially 36 to 39 per hour<br>• Could enable aircraft pairs allowing a heavy/B757 to lead on 28L. NextGen controller tools that will come on-line provide for time based spacing, enabling 0.6 nm stagger for CSPO<br><br>*Note: FAA Order 7110.308A evaluation of the improved vertical separation required* |

 

# 7 Next Steps

This project demonstrated the capability and benefits of RNP to GLS procedures and provided insights to procedure design and best practices for RNP to GLS operations. This section discusses items to be addressed prior to any GLS implementation and a status of GLS proliferation worldwide. As such, IAPs in this demonstration are conceptual charts. Additional work is required to develop certified procedures acceptable for operational service. The entire project team gained valuable insights into procedure design and operational implementation.

## 7.1 Instrument Approach Procedure Implementation at SFO

### 7.1.1 GLS P RWY 10L

In the near term, a complete TERPS analysis of the runway 10L final approach terrain should be performed to provide a current assessment of the obstacle field. This information would determine the appropriate minima/decision altitude for an RNP to GLS approach to runway 10L.

### 7.1.2 GLS R RWY 19R

In the near term, the airport could develop an RNAV RNP AR IAP over the GLS R track with the same vertical profile. This would improve operational efficiency and reduce minima compared to operations today. Implementation of this procedure would represent the first step toward simultaneous approaches to runways 19L and 19R. The demonstration identified the need to revise the GLS 19R base to final to de-conflict with the OAK RWY 12 final approach. This can be accomplished by moving the RF leg south by 0.5 nm. Figure 34 shows a revised GLS R 19R procedure depicting the modified RF leg.


*Figure 34: GLS R RWY 19R Revised Procedure*

### 7.1.3 GLS W RWY 28R & GLS V RWY 28R Revised Procedures

Modifications are required to both procedures to 28R (GLS W and GLS V) to further de-conflict with the Oakland final approach to OAK RWY 12/30. At direction from NCT, the GLS W 28R and GLS V 28R approaches were modified to a shorter turn into final.

 

The original RNP to GLS procedures, as flown in the demo, conflicted with the final approach to Oakland RWY 30. Figure 36 and 36 show the drafts of the revised procedures.

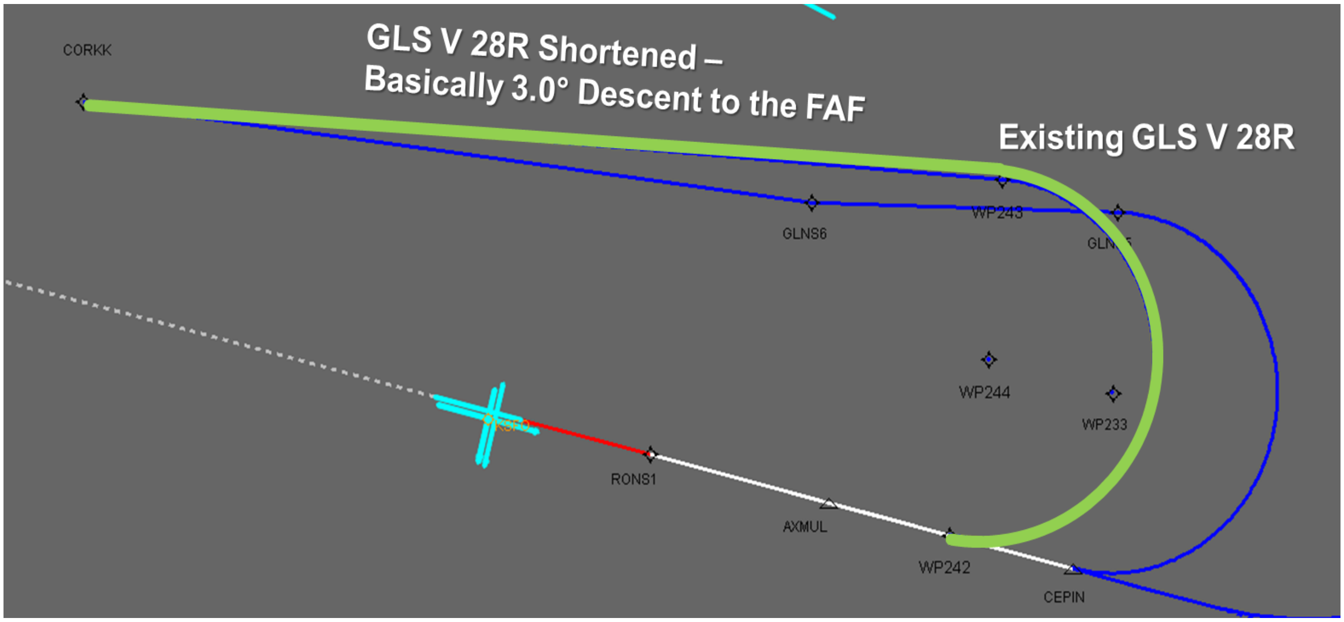


*Figure 36: Revised GLS V RWY 28R CSPO Procedure*

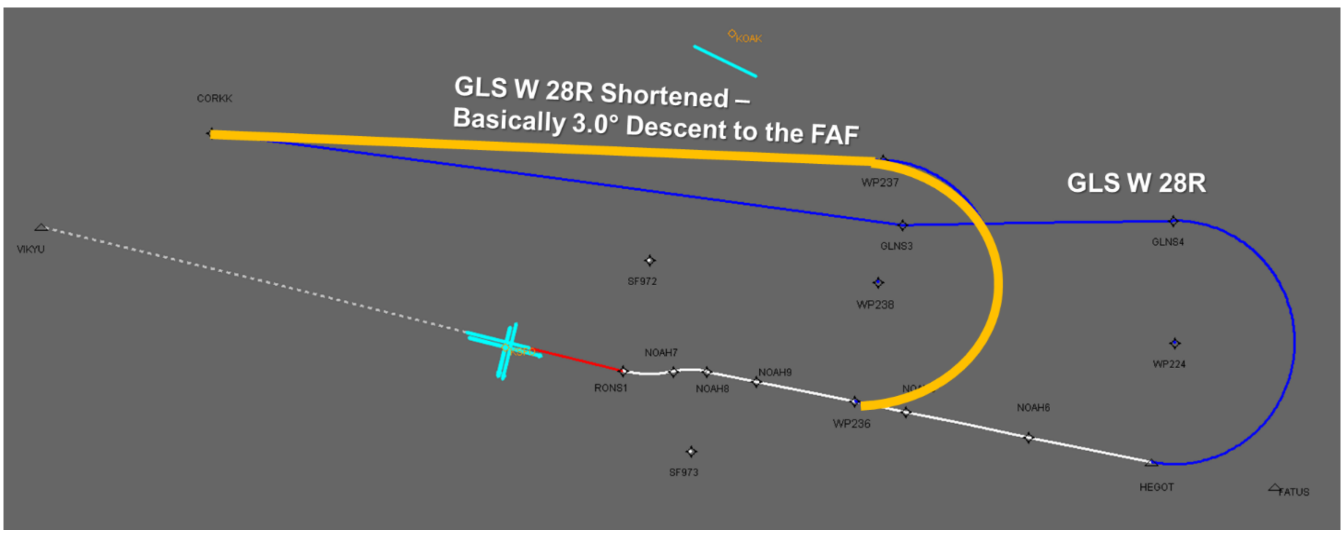


*Figure 35: Revised GLS W RWY 28R SOIA Procedure*

 

## 7.2 ATC and GBAS Considerations for RNP to GLS Operational Implementation at SFO

### 7.2.1 GBAS Acquisition and Installation

In the Performance Based Navigation (PBN) Strategy 2016 document,[16] the FAA states GLS is a non-federal system. It does state that the FAA has supported development of GLS equipment, standards and implementations, and will continue to do so in the future. Currently there are certified systems providing revenue service at Newark, and Houston, and plans for others funded by a number of airports in the national airspace. The FAA is developing a cost-benefit analysis to determine the viability of FAA acquisition of GBAS as a federal system. The SFO RNP to GLS demonstration has shown the potential value of these procedures to enable improved closely spaced parallel operations at runways spaced less than 2500 feet apart, and also how it can be used in concert with RNP for both environmental and air traffic improvements to under-served runways. The work of this demonstration will be made available to the FAA cost benefit analysis team.

The demonstration used a portable GBAS which is only approved for functional tests, check flights and demonstrations. PBAS is not suitable for revenue passenger operations. A design approved GBAS would be required for operational approval of the procedures.

### 7.2.2 Established on RNP (EoR) Operations

There is an opportunity for the airlines and NCT to take a proactive role in developing plans and implementing Established on RNP (EoR) operations in the SFO Bay Area metroplex. This action is based on the current FAA PBN Strategy 2016 document. In the document the FAA indicates it will implement EoR at a key sites in the near term. This SFO RNP to GLS demonstration has resulted in Air Traffic/Airline discussions regarding the potential benefits to SFO operations. As an example, utilizing the CORKK transition to GLS V 28R in conjunction with ILS 28L may be of interest considering the vertical path separation component introduced with the RNP to GLS design. Adoption of EoR procedures may offer benefits for NCT, airports and the airlines based on the results of this RNP to GLS demonstration.

[16] https://www.faa.gov/nextgen/media/PBN_NAS_NAV.pdf

## 7.3 Future Considerations and Rulemaking

### 7.3.1 Airport Infrastructure

One benefit of GLS is the ability to establish multiple precision approaches with different glideslope angles and touchdown points. An ILS only provides one glideslope and one localizer per installation. This may allow aircraft to safely avoid wake vortices from aircraft approaching the same or closely spaced parallel runways. MITRE Corporation has reviewed and published findings regarding the potential of wake vortex enhancements.[17]

For this demonstration, runway lighting to identify the secondary touchdown point was in place to provide a visual cue of the runway aim point for the pilots. The airport provided truck-mounted construction lights positioned at a location 2000 feet from the runway 28R threshold. In a previous implementation of alternate touchdown points at Frankfurt Airport, a temporary lighting was installed to identify the secondary touchdown. The concept was called HALS / DTOP or High Approach Landing System / Dual Threshold Operation (though it is no longer in use today)[18]. Standards for lighting and marking have not yet been established for alternate touchdown points enabled by GLS.

### 7.3.2 Descent Rates from Increased Glideslopes

Boeing production aircraft (737 NG, 747-8, 777, 787) are certified of autoland up to $3.25^0$. One question that arose was the difference in descent rates with increased glideslopes. Today in the US, the majority of precision approaches to runway ends are ILS set to a 3° glidepath. Approaches between 2.75° and 3.5° are considered standard for airline operations, but are uncommon except due to local constraints (e.g., terrain). For example, the approaches to Runway 27 at San Diego International Airport[19] have a glidepath of 3.5°. Descent rates, also known as vertical speed, vary with weight, reference speeds, glideslope and flap configuration. For the 737-900ER, a range of reference speeds is about 110 knots (Flaps 40, light airplane) up to about 155 knots (Flaps 30, heavy airplane.) The difference between a Flap 40 and Flap 30 approach is about 7 knots, which translates to a difference of about 40 feet per minute. These factors need diligent consideration when exercising GLS capability to support arrivals with increased glideslopes.

## 7.4 RNP to GLS Rulemaking – Guidance Material Development

### 7.4.1 GBAS Standards

Global standards for GBAS are in work. Boeing and other aviation stakeholders are actively supporting development of these standards. At ICAO, standards and recommended practices (SARPs) for GBAS GAST D (GAST D provides CAT III minima) supporting CAT II/III operations were completed and validated in August 2016. GAST D SARPs will be translated and presented to the ICAO Navigation Systems Panel in December 2016, and if accepted will go to the Air Navigation Commission for State Letter. States have two years to review and GAST D SARPs will be effective December 2018. At Radio Technical Commission for Aeronautics (RTCA), minimum operational performance standards (MOPS) [document DO-253D MOPS] and interface control documents (ICD) [document DO-246E ICD] are in work, and updates will be completed in 2Q2017. At the FAA, a draft of Airworthiness Criteria AC 120-xLS expected to be released by 1Q2017.

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[17] https://www.mitrecaasd.org/library/one_pagers/wake.pdf

[18]
http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=9&cad=rja&uact=8&ved=0ahUKEwjDwfPOqrfPAhUOxmMKHWhJDfkQFghEMAg&url=http%3A%2F%2Fwww.mxpairport.it%2Ffile_download%2F403%2FFra.pdf&usg=AFQjCNERMwLPKPnqZJ2u81_JWVsiVD1nXw&sig2=9BaNegq18rVeEvpug4oCoA

[19] IAPs to RNAV (GPS) RWY 27 and LOC RWY 27

### 7.4.2 Procedure Design Standards

One of the primary goals of the FAA and industry Performance-Based Operations Aviation Rulemaking Committee (PARC) Navigation Working Group is to develop criteria for RNP to xLS (xLS means ILS or GLS) IAP designs to support FAA authorization of these procedures. The primary IAP design criteria document is FAA Order 8260.58A (TERPS for RNAV). The current published RNP to GLS IAP design criterion addresses both the lateral track and vertical performance requirements (non-standard day mitigation) for general use by a wide range of fleet navigation capability.

The PARC Navigation Working Group is currently engaged in addressing the type procedure design utilized during the SFO demonstration, RNP RF leg type linking to the GLS final approach point (FAP), which requires a specific airplane navigation systems capability. The final criteria supporting the IAP design as utilized at SFO RNP to GLS demonstration are expected in 2017. At the recommendation of the PARC, the FAA will publish a revision to FAA Order 8260.58A[20] to describe procedure design changes required for RNP to xLS operations in 2017. Follow on PARC activity will support development of the FAA Flight Standards training, RNP to GLS charting guidance material and navigation database considerations.

It is anticipated that these criteria will be adopted by the FAA and presented in various ICAO venues by FAA Flight Standards by mid-2017. Similarly, International Civil Aviation Organization (ICAO) Instrument Flight Procedures Panel (IFPP) Pans Ops 2016[21] amendment included initial RNP-xLS straight in criteria. The future ICAO Pans Ops amendment will include the RF legs and RNP AR.

## 7.5 Boeing GLS Equipage

On Boeing models, GLS CAT I functionality is an optional feature on the 737 NG and the 737 MAX, and is baseline on the 747-8, 777X and 787. Retrofit solutions are under study for the 777. The fleet of Boeing aircraft worldwide that are capable of GLS is rapidly growing; over 1500 aircraft are equipped today and nearly half of all new deliveries are GLS equipped. All Boeing aircraft so equipped are certified for GLS autoland capability. Boeing is pursuing GLS CAT III for potential future offerability. CAT III GBAS ground station standards and equipment are under development.

[20] http://www.faa.gov/documentLibrary/media/Order/FAA_Order_8260.58A.pdf
[21] http://www.icao.int/safety/airnavigation/OPS/Pages/flsannex.aspx

## 7.6 GLS Growth

Airlines, airports and air navigation service providers are exploring the applicability of RNP to GLS operations to support their future plans to increase capacity, efficiency and enable cost effective precision approaches. Aircraft avionics and airport equipage are reaching a tipping point as GLS CAT I capability is becoming standard on new aircraft models. Both domestically and internationally, RNP to GLS procedures are considered a necessary technology to support future operational needs.

Major airports in the United States including John F. Kennedy International Airport, LaGuardia Airport, Chicago O'Hare International Airport, Hartsfield-Atlanta International Airport, and Seattle-Tacoma International Airport are considering GLS operations in the next five years. Internationally, many nations have proposed GLS implementation plans in the near term. China views GLS as a way to "leapfrog" ILS at new airports. In 2015, China's aviation authority published a Performance Based Navigation Implementation Roadmap, which included GLS and other advanced satellite capabilities, to enhance efficiency and airport access. GBAS and GLS trials and research in Europe, including Frankfurt, Zurich and Toulouse, are supported in part by Single European Sky Air Traffic Management (ATM) Research (SESAR), a public-private partnership to overhaul the air traffic in Europe. GLS studies are underway in the UK, Norway, Poland, Switzerland, Sweden and France. In Germany, there are GBAS units operational at Frankfurt Airport (FRA) and Bremen Airport (BRE). Bremen published the first public European RNP to GLS procedure in early 2016. GBAS installations at Houston (IAH), Newark (EWR), Sydney (SYD), and FRA provided valuable insights into the operational benefits of GLS. During Winter Storm Jonas, in January 2016, ILS guidance was unavailable at EWR due to snow accumulation. The GBAS continued providing GLS service allowing United Airlines to continue landings with GLS capable aircraft.

ILS is the predominant precision approach capability at airports today. However, there are limitations to these systems: they require periodic flight checks which can impact airport operations as each ILS procedure must be flown in its entirety. ILS requires large, unobstructed areas to prevent signal interference from terrain or structures, and a single ILS provides only one glideslope and touchdown point per single runway end. On the other hand, GBAS flight checks are less invasive as they only require a single flight check to confirm that the system is operational, and a single GBAS supports multiple approaches with different glideslopes and touchdown points, and does not have critical areas like ILS.

Simultaneous parallel operations, like SOIA and CSPO, are key enablers to maintain capacity and efficiency in low ceiling and visibility conditions. Wake turbulence mitigation for parallel runway operations with different glideslopes is in place today, however the additional flexibility provided with GBAS offers many more approach alternatives with a single facility. Maintaining wake turbulence separation criteria are essential for safety. Lastly, it is critical that all landing aircraft be stabilized on the lateral and vertical guidance towards an aiming point on the runway. With existing precision approach capability, meeting stabilized approach criteria requires longer, straight-in, final segments to allow sufficient time for ILS signal capture and stabilization.

RNP procedures alone can provide community noise and emissions reduction. By overflying unpopulated areas, like industrial zones or natural waterways, noise is moved away from the general public. While both RNP and GLS can be used separately, the most operational benefits are achieved when an RNP approach terminates in a GLS final segment. With RNP to GLS approaches enabled by a GBAS, it is possible to provide precision approach capability to runways near to natural or man-made obstruction, differing glideslopes, and different displaced thresholds. The added flexibility from RNP to GLS procedures allows added capability for wake turbulence mitigation. In addition aircraft require less time to meet stabilized approach criteria which in turn allows for a shorter final segment which can reduce track miles flown, and therefore reduce fuel burn and emissions. Airports and airlines are likely to press for increased RNP to GLS operations. The demonstration flights by Delta and United on August 27th, 2016, highlighted the potential of RNP to GLS capabilities.

# 8 Acronyms

| | |
|---|---|
| AC | Advisory Circular |
| AGL | Above Ground Level |
| ATC | Air Traffic Control |
| BCOP | Boeing Climbout Performance Tool |
| CAT | Category |
| CSPO | Closely Spaced Parallel Operations |
| DA(H) | Decision Altitude [precision approaches] |
| DAL | Delta Air Lines |
| DTT | Distance-to-Threshold |
| eCab | Engineering Cab |
| EoR | Established on RNP |
| FAA | Federal Aviation Administration |
| FAC | Final Approach Course |
| FAP | Final Approach Point |
| FAS | Final Approach Segment |
| FOQA | Flight Operations Quality Assurance |
| GBAS | Ground Based Augmentation System |
| GLONASS | Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russian GPS) |
| GLS | GNSS Landing System |
| GNSS | Global Navigation Satellite System |
| IAP | Instrument Approach Procedure |
| ICAO | International Civil Aviation Organization |
| ICD | Interface Control Document |
| IF | Initial Fix |
| IFPP | Instrument Flight Procedure Panel |
| IFR | Instrument Flight Rules |
| ILS | Instrument Landing System |
| IMC | Instrument Meteorological Conditions |
| INM | Integrated Noise Model |
| LDA | Localizer Type Directional Aid |
| LNAV | Lateral Navigation |
| LOC | Localizer |
| LR | Line Replaceable Unit |
| MDA(H) | Minimum Descent Altitude [Height for non-precision approaches] |
| MOPS | Minimum Operational Performance Standards |
| NCT | NORCAL TRACON |
| NDB | Navigation Database |
| NG | Next Generation |
| nm | Nautical Miles |
| NMT | Noise Monitor Terminals |
| NORCAL | Northern California |
| NTZ | Non-Transgression Zone |
| OAK | Oakland International Airport |
| PAPI | Precision Approach Path Indicator |
| PBN | Performance Based Navigation |
| PARC | Performance-Based Operations Aviation Rulemaking Committee |

Acronyms (Continued)

| | |
|---|---|
| PBAS | Portable GBAS |
| PFD | Primary Flight Display |
| PRM | Precision Runway Monitor |
| QAR | Quick Access Recorder |
| RA | Radio Altitude |
| RF | Radius to Fix |
| RNAV | Area Navigation |
| RNP AR | Required Navigation Performance Authorization Required |
| RNP | Required Navigation Performance |
| RTCA | Radio Technical Commission for Aeronautics |
| SARP | Standards and Recommended Practices |
| SESAR | Single European Sky Air Traffic Management (ATM) Research |
| SFO | San Francisco International Airport |
| sm | Statute Miles |
| SOIA | Simultaneous Offset Instrument Approaches |
| SOP | Standard Operating Procedure |
| STAR | Standard Terminal Arrival Route |
| TERPS | Terminal Instrument Procedures |
| TF | Track to Fix |
| TRACON | Terminal Radar Approach Control |
| UAL | United Airlines |
| VFR | Visual Flight Rules |
| VMC | Visual Meteorological Conditions |
| VNAV | Vertical Navigation |
| xLS | GLS, ILS or Microwave Landing System (MLS) |

# Appendix A– 27-Aug-16 Flight Sequence

| Cond. No. | A/P | GLS Channel/ILS Freq | ID | Procedure | Flap | Notes |
|---|---|---|---|---|---|---|
| **.201** | DL | 21582 | G10P | GLS P RWY 10L | F40 | |
| **.202** | UA | 21582 | G10P | GLS P RWY 10L | F40 | |
| **.203** | DL | 21993 | G19R | GLS R RWY 19R | F30 | |
| **.204** | UA | 21993 | G19R | GLS R RWY 19R | F30 | |
| **.205A** | DL | 109.55 | ISFO | ILS RWY 28L | F30 | SOIA |
| **.205B** | UA | 20760 | G28W | GLS W RWY 28R | F30 | SOIA |
| **.206A** | DL | 109.55 | ISFO | ILS RWY 28L | F30 | CSPO |
| **.206B** | UA | 21171 | G28V | GLS V RWY 28R | F40 | CSPO |
| **.207A** | DL | 111.7 | ISFO | ILS RWY 28R | F30 | Baseline |
| **.207B** | UA | 111.7 | ISFO | ILS RWY 28R | F40 | Baseline |
| **.208A** | DL | 20760 | G28W | GLS W RWY 28R | F30 | SOIA |
| **.208B** | UA | 109.55 | ISFO | ILS RWY 28L | F30 | SOIA |
| **.209A** | DL | 21171 | G28V | GLS V RWY 28R | F30 | CSPO |
| **.209B** | UA | 109.55 | ISFO | ILS RWY 28L | F30 | CSPO |

# Appendix B – Demonstration Sequence and Notes Sheet

**INTRODUCTION**

The objective of this flight is to demonstrate RNP to GLS instrument approach procedures

**GENERAL INFORMATION**

- **Planned Crew and Non-Flight Crew Personnel Onboard (#)**
  - **DAL : 6**
  - **UAL : 8**

- **Call signs**
  - **DAL : Delta 9984**
  - **UAL : United 2138**
  - **PBAS: Boeing PBAS**

- **Weather Limitations**
  - Maintain visual clearance of traffic and obstacles for all GLS procedures
  - Minimum weather requirement for RWY 28R GLS (suggested 3000 feet and 5 statute miles)
  - Minimum vectoring altitudes (MVA) chart is provided for decision making reference marginal ceiling/visibility conditions

- **Demo Requirements**
  - Install Boeing-Jeppesen provided navigation database to DAL and UAL
  - PBAS broadcasting all GLS procedures
  - 2–way communications with PBAS and the aircraft
  - Auxiliary side line lighting at the 28R 2000 feet displaced threshold point

- **General Notes**
  - Follow airline SOP (DAL and UAL)
  - GLS W 28R – arm approach (or LOC) inbound from HEGOT to avoid premature LOC capture

- **Required Data**
  - Check GPS DOP
  - **Manual Data**: Subjective notes about the RNP/GLS procedures and comments from the crew, ATC, and CT.
  - **Flight Recorder Data:** downloaded after the flight

**PRE PREFLIGHT**

- Install Boeing-Jeppesen provided nav database to DAL and UAL A/Ps
- **Deploy PBAS Team (Launch Time - 2hrs)**

**SEQUENCE**

- Communications Check
  - Tower to assign VHF frequency for aircraft to aircraft communication (128.65)
  - Flight Coordination Mike C.
    - Contact SFO Tower Supervisor – 650-876-2722 - Hit 5 when it answers
    - Contact NCT Operations Manager – 916 366 4080
    - Contact PBAS Crew – VHF Radio (123.15)
  - Recording media on

| Cond. No. | Procedure |
|---|---|
| .101 | Confirm database (preferably before launching the entire crew to both aircraft and PBAS); load the approaches and confirm the fixes (altitudes and speeds)<br><br>TBC NDB # ______________________________ |
| .102 | Tune each GLS approach and verify proper decoding of approach information on PFD (Approach ID/ course runway and reasonable distance to threshold)<br><br>• 20760 GLSW/ 284 RW28R xx.x<br>• 21171 G28V/284 RW28R xx.x<br>• 21582 G10L/104 RW10L xx.x<br>• 21993 G19R/194 RW19R xx.x<br><br>Confirm with the other aircraft all GLS approaches are verified operational |

- Takeoff

| Cond. No. | A/P | GLS Channel or ILS Freq | ID | Procedure | Flap | Notes |
|---|---|---|---|---|---|---|
| .201 | DL | 21582 | G10P | GLS P RWY 10L<br><br>• Start IAP from STINS, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Expect Missed approach heading 340 / 3000 feet | F40 | |
| .202 | UA | 21582 | G10P | GLS P RWY 10L<br><br>• Start IAP from STINS, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Expect Missed approach heading 340 / 3000 feet | F40 | |
| .203 | DL | 21993 | G19R | GLS R RWY 19R<br><br>• Start IAP from WESLA / 6000 feet, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Perform the GLS R RWY 19R procedure<br>• Terminate go around 100 feet RA<br>• Expect Missed approach to 340 / 3000 feet | F30 | *NCT wants video from WESLA |
| .204 | UA | 21993 | G19R | GLS R RWY 19R<br><br>• Start IAP from WESLA / 6000 feet, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Perform the GLS R RWY 19R procedure<br>• Terminate go around 100 feet RA<br>• Expect Missed approach to 340 / 3000 feet | F30 | |

| Cond. No. | A/P | GLS Channel or ILS Freq | ID | Procedure | Flap | Notes |
|---|---|---|---|---|---|---|
| .205A | DL | 109.55 | ISFO | ILS RWY 28L<br>• Start IAP HEMAN, or as instructed by ATC<br>• Terminate the ILS approach with a go-around at 100 feet RA<br>• Expect missed approach heading 265 / 3100 feet | F30 | SOIA |
| .205B | UA | 20760 | G28W | GLS W RWY 28R<br>• Start IAP CORKK / 11000 feet or as instructed by ATC<br>• Verify proper GLS approach information on PFD<br>• Terminate the GLS W approach with a go-around at 100 feet RA<br>• Expect Missed Approach RW Heading / 3000 feet | F30 | SOIA |
| .206A | DL | 109.55 | ISFO | ILS RWY 28L<br>• Start IAP HEMAN, or as instructed by ATC<br>• Terminate the ILS approach with a go-around at 100 feet RA<br>• Expect missed approach heading 265 / 3100 feet | F30 | CSPO |
| .206B | UA | 21171 | G28V | GLS V RWY 28R<br>• Start IAP from CORKK, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Perform the GLS V RWY 28R procedure<br>• Terminate the approach with a go-around at 100 feet RA<br>• Expect Missed Approach RW heading / 3000 feet | F40 | CSPO |

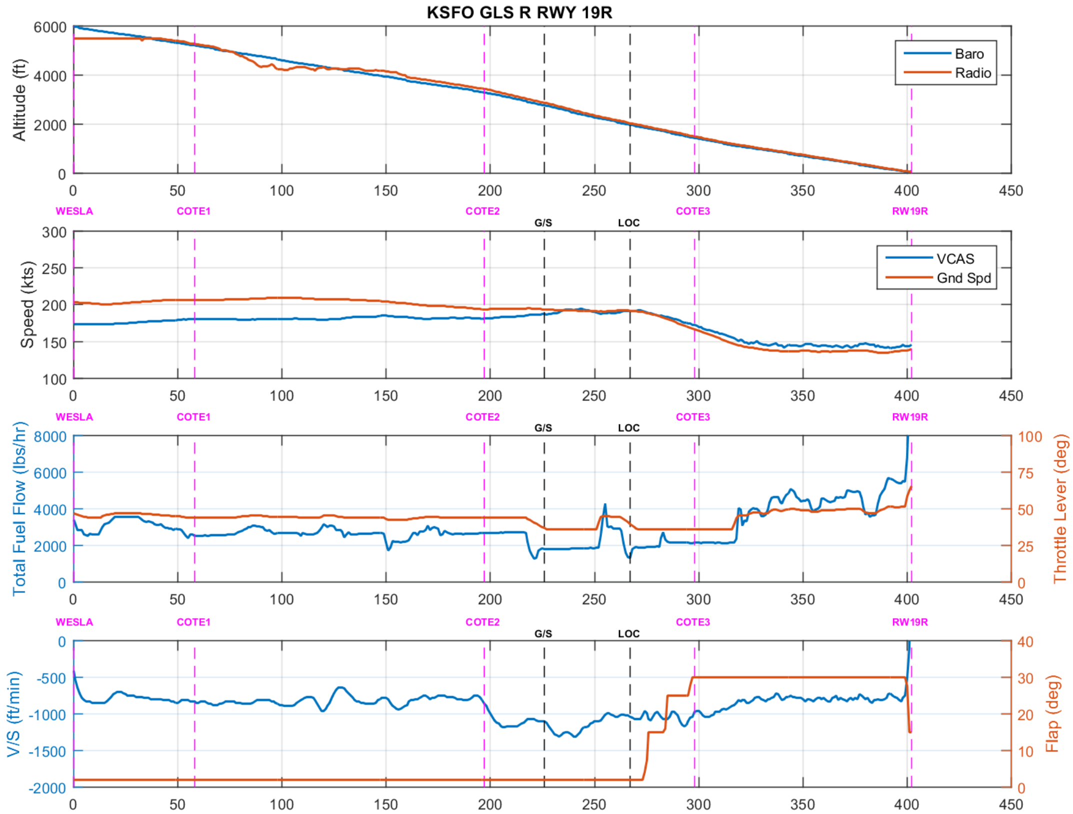
| Cond. No. | A/P | GLS Channel or ILS Freq | ID | Procedure | Flap | Notes |
|---|---|---|---|---|---|---|
| .207A | DL | 111.7 | ISFO | ILS RWY 28R<br><br>• Start IAP CEPIN, or as instructed by ATC<br>• Terminate the ILS approach with a go-around at 100 feet RA<br>• Expect Missed Approach RW heading / 3000 feet | F30 | In-trail (3-4) miles visual<br><br>Expect right turn |
| .207B | UA | 111.7 | ISFO | ILS RWY 28R<br><br>• Start IAP CEPIN, or as instructed by ATC<br>• Terminate the ILS approach with a go-around at 100 feet RA<br>• Expect Missed Approach RW heading / 3000 feet | F40 | In-trail (3-4) miles visual<br><br>Expect left turn |
| .208A | DL | 20760 | G28W | GLS W RWY 28R<br><br>• Start IAP from CORKK / 11000 feet, or as instructed by ATC<br>• Verify proper decoding of approach information in PFD<br>• Terminate the GLS W approach with a go-around at 100'RA<br>• Expect RW heading / 3000 feet | F30 | SOIA |
| .208B | UA | 109.55 | ISFO | ILS RWY 28L<br><br>• Start IAP HEMAN, or as instructed by ATC<br>• Terminate the ILS approach with a go-around at 100 feet RA<br>• Expect Missed Approach heading 265 / 3100 feet | F30 | SOIA |

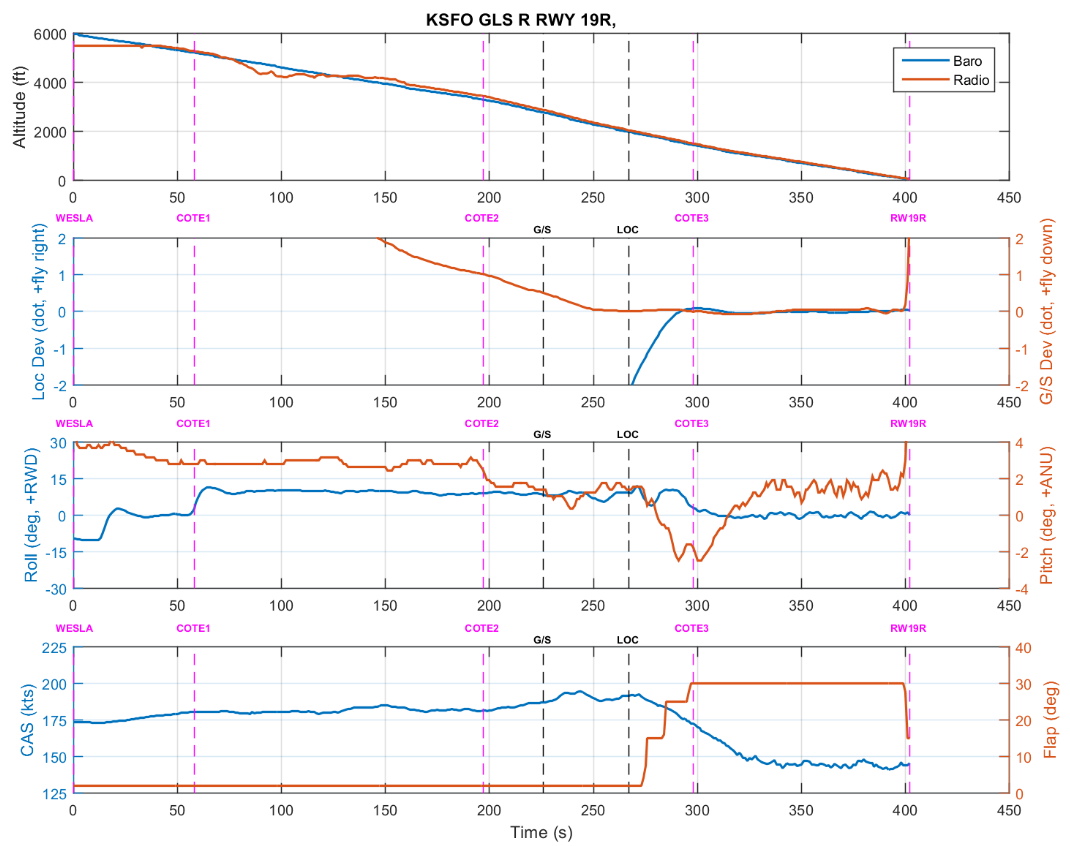
| Cond. No. | A/P | GLS Channel or ILS Freq | ID | Procedure | Flap | Notes |
|---|---|---|---|---|---|---|
| .209A | DL | 21171 | G28V | GLS V RWY 28R<br><br>• Start IAP from CORKK / 11000 feet, or as instructed ATC<br>• Verify proper decoding of approach information in PFD<br>• Terminate the GLS V approach with a full stop | F30 | CSPO |
| .209B | UA | 109.55 | ISFO | ILS RWY 28L<br><br>• Start IAP HEMAN, or as instructed by ATC<br>• Terminate the ILS approach with a full stop | F30 | CSPO |

- **Taxi back to respective gates/stands**
- **Recover PBAS crew**
- **Post Flight: Convene at designated airport location to record thoughts/impressions and address any immediate concerns**

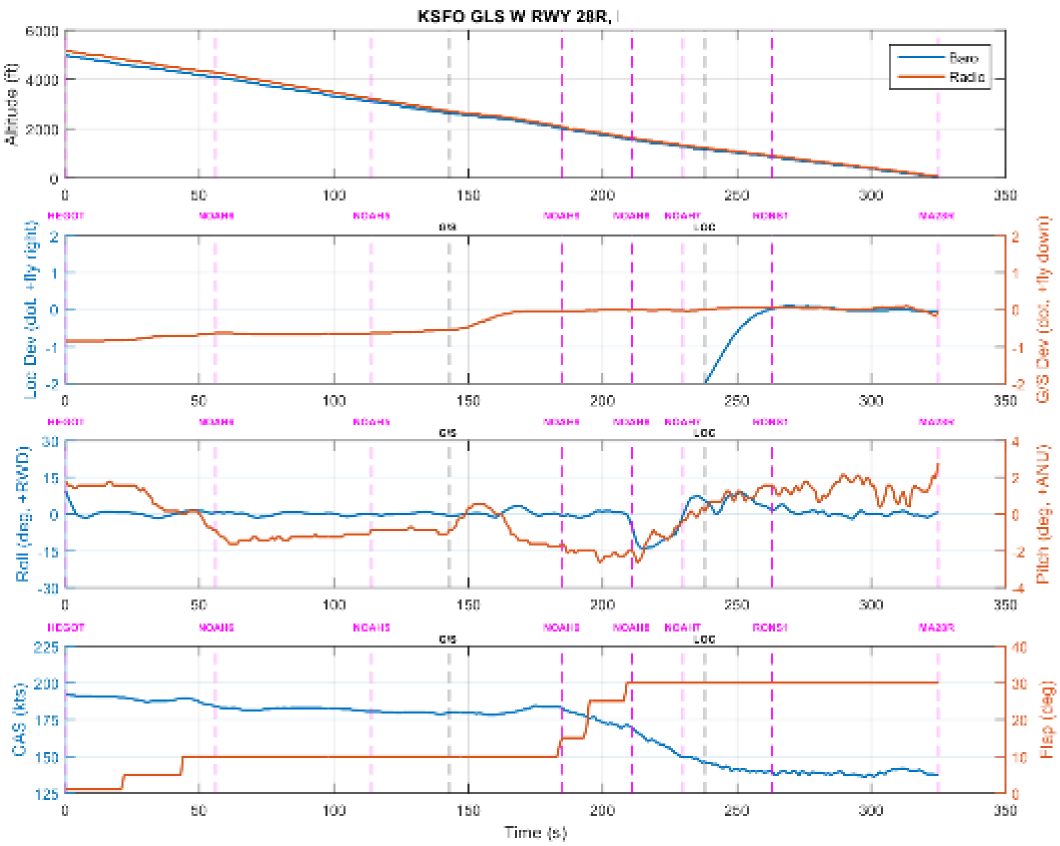
# Appendix C – AFDS Performance GLS R 19R

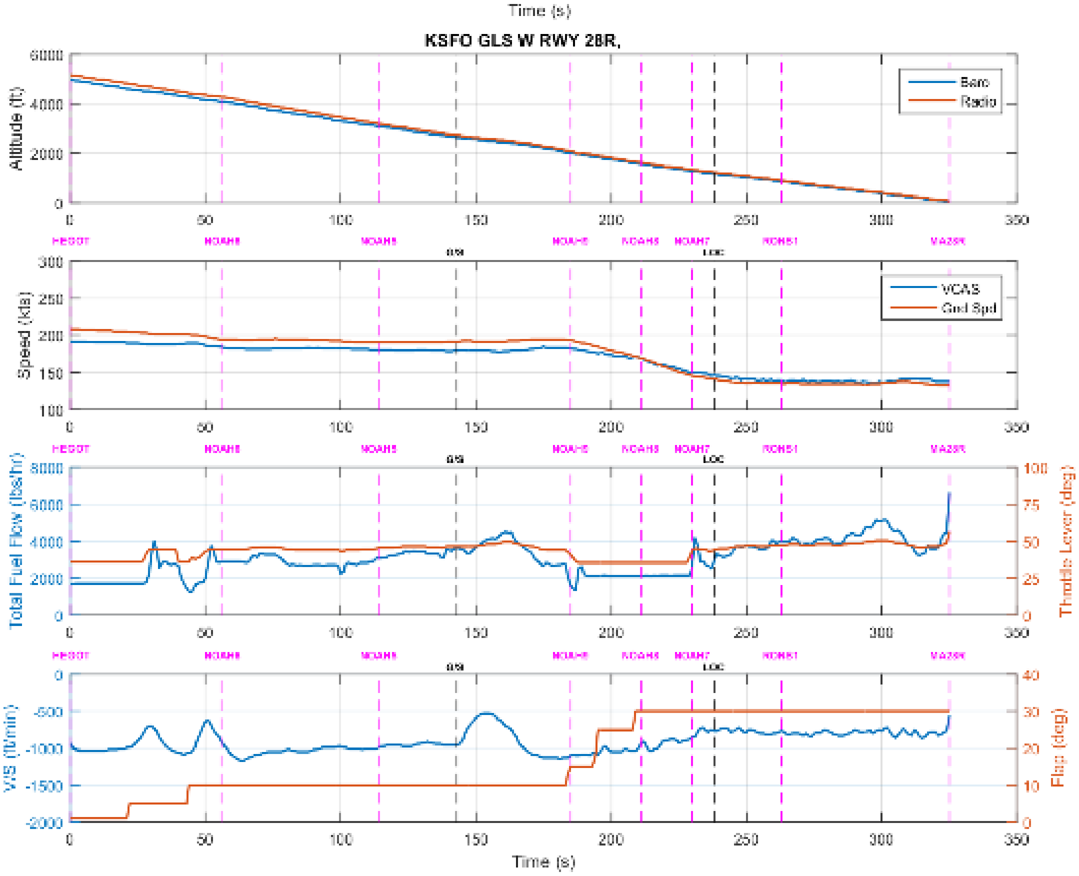


# Appendix D – AFDS Performance GLS W 28R



# Appendix E – AFDS Performance GLS V 28R